

HVDC TRANSMISSION SYSTEM FOR REMOTE ALASKA APPLICATIONS

Phase I: Preliminary Design and
Feasibility Analysis

FINAL REPORT

Prepared for:

Denali Commission



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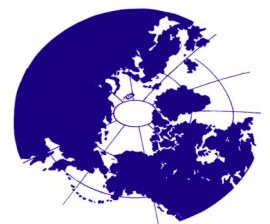
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FOREWORD

This report presents the results of Polarconsult's review and analysis of the technical feasibility, economic feasibility, challenges, and advantages of using high-voltage direct current (HVDC) electrical interties to connect remote Alaska communities with each other and with local energy resources.

The completed investigations have found that this HVDC system and approach can offer significantly lower costs for remote low-power electrical interties, and continued development is recommended.

Polarconsult acknowledges and appreciates the support and contributions of the many individuals and entities that have contributed to this project. Their support, insights, experience, and technical analysis are invaluable to the continuing effort to bring this technology to Alaskans.

Members of the team involved in this first phase of HVDC intertie development are:

Denali Commission

Funding Agency

Alaska Village Electric Cooperative, Inc. *Project Administrator, Technical Advisor*

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Principal Investigator, Report Author

Princeton Power Systems, Inc.

Converter Design, Construction, Testing

About the Cover Images:

Image at upper left is an AC-Link™ AC power converter cabinet developed by Princeton Power Systems, Inc. The cabinet is similar in size and appearance to the HVDC converter cabinet described in this report.

Image at lower left is an artistic rendering of an overhead SWER HVDC intertie traversing typical Alaska tundra conditions.



EXECUTIVE SUMMARY

This report presents the findings of the first phase of a project to develop a one-megawatt High-Voltage Direct Current (HVDC) Transmission System for remote Alaska applications. The Phase I objectives were to:

- Confirm the technical feasibility of the HVDC to AC power converter technology by designing, building, and testing a bench-top prototype converter.
- Confirm the economic feasibility of the HVDC transmission system for remote Alaska applications by determining the commercial cost of the converter, the converter efficiency, and the probable overall costs of an HVDC system.
- Determine if the feasibility of the HVDC technology and system warrant continued development.

Phase I has successfully met all objectives. The converter technology is technically viable, and the transmission system is economically feasible. Probable costs for a conceptual 25-mile overhead HVDC intertie indicate life-cycle cost savings of up to 28% compared with a conventional three-phase AC intertie. Based on Phase I results, continued development of this system is recommended.

This innovative electrical transmission technology can significantly decrease the cost of remote electrical interties in Alaska compared with the AC interties now being built.

Reducing the cost of these interties can enable more remote villages to be connected together, building economies of scale that can reduce the cost of energy in these villages. The larger electrical loads reached by these 'mini-grids' can justify development costs for more local energy resources, such as wind, hydro, biomass, geothermal, hydro-kinetic, gas, and coal.

Examples of potential applications of this technology include:

- Connecting Bethel and nearby villages with a wind farm along the Bering Sea coast.
- Connecting 25 southwestern communities to a 25-megawatt (MW) geothermal plant near King Salmon.
- Distributing low-cost energy from the proposed Toshiba nuclear 'battery' in Galena to neighboring villages along the Yukon River.
- Connecting Nome to a geothermal plant at Pilgrim Hot Springs.
- Completing connections in the Southeast Intertie via an affordable HVDC submarine cable.
- Connecting North Slope communities such as Atkasuk with Barrow to share in the low-cost electricity derived from Barrow's gas fields.



Based upon the outcome from Phase I of this HVDC project, the following activities are recommended for continued action and attention:

- Work with stakeholders to define a project for Phase III of this project and also to incorporate this technology into the State's master planning efforts for energy planning and policy. This HVDC technology can be ready for widespread commercial application as early as 2011, and the state should be prepared to use it. The survival of many of our villages may well depend on it.
- Continue to develop a statewide energy plan. The energy plan needs to consider the implications of affordable HVDC transmission interties, as they will dramatically change the outcome of the planning efforts for Alaska's remote communities. Local interties, larger energy projects, and lower energy costs are expected outcomes of using this more affordable transmission system.
- Start to identify and secure transmission alignments for the necessary interties. Also, long-lead generation projects need to be prioritized and initiated.
- Build stakeholder support for state amendments to the NESC that will allow use of SWER circuits under appropriate conditions. If used properly, SWER circuits will reduce the installed costs of remote transmission systems without any negative impacts.
- Research communications options that may be able to be combined with HVDC and other intertie systems.



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ACRONYMS AND TERMINOLOGY

A, a, i	amperes or amps. A measure of the amount of electrical current flowing through a circuit. A typical household circuit is rated for 20 amperes.
AC	alternating current. The form of electricity commonly used in homes and businesses in which the current and voltage oscillate at a frequency of 60 cycles per second. (The frequency in some nations is 50 cycles.)
albedo	The extent to which an object diffusely reflects light.
ANSI	American National Standards Institute
ASCE	American Society of Civil Engineers
AVEC	Alaska Village Electric Cooperative, Inc.
AW	Alumoweld. A type of cable used in electrical systems. Each strand of the cable consists of a steel core with a layer of aluminum extruded over it during the pulling and drawing process. The steel core provides increased strength, and the aluminum exterior provides better corrosion protection and increased electrical conductivity.
bandwidth	A measure of the data transfer capability of a given communications method. Units of bandwidth can vary but are generally bits per second.
bipolar	A type of direct current circuit that uses two wires to transmit energy. Bipolar circuits operate one wire ('pole') at a positive potential and the second pole at a negative potential relative to ground (e.g., +/- 600,000 volts). These circuits normally also have an earth return pathway or a dedicated ground conductor that is used to compensate for any imbalance on the two poles and also serves as a temporary return pathway if the negative or positive pole is out of service for any reason.
bosun's chair	A rigid or flexible chair seat that is designed for a person to sit in and be hoisted up by a cable or rope. The chair is used as an easy way to lift someone up a pole or similar structure.
circuit	A circuit provides an electrical pathway from a point of energy supply (e.g., a generator or battery) to a point of energy use (e.g., motor, lighting, etc.), and then back to the point of supply. Without a complete pathway from supply to use and back, the circuit will not function. The pathway can take many forms. Most commonly it is made of metallic (copper or



aluminum) wires, but it can also use water, the earth, or other materials. These other materials are most often used on the return pathway back to the point of supply, where the voltage differential relative to the surrounding environment is low.

conductor A typically metallic wire or cable that is designed and fabricated to conduct electricity between two locations.

converter An electrical device that is callable of transforming electricity from AC to DC and/or from DC to AC.

DC direct current. Direct current is the form of electricity commonly used in battery powered devices such as cars, flashlights, etc. The current does not appreciably vary with time.

distribution-class

Refers to lower-voltage electrical systems. Definitions vary, but systems operating at or below nominal 35 kV are generally classified as distribution-class. Most remote Alaska interties function as transmission systems, but operate at distribution-class voltages, typically 14.4 kV.

earth return A means of completing an electrical circuit by using the earth as a return path instead of a second wire. In many nations, this approach is frequently used in rural areas where (1) the cost to install a second wire for the return path is prohibitively high and (2) the lack of buried utilities ensures that technical issues with ground return are minimized.

EPR ethylene propylene rubber

FO fiber optics. A communications method that consists of sending pulses of light down glass fibers.

GVEA Golden Valley Electric Association, Inc.

hertz A unit of how rapidly something oscillates, rotates, or repeats. One hertz is equal to one complete cycle per second. Alternating current electrical systems in the U.S. operate at 60 hertz, or 60 cycles per second.

high-impedance ground fault

A fault or short circuit between a high voltage wire and ground. An example of a high-impedance ground fault would be a conductor that falls to the ground without breaking, landing on ice or ice-rich soils.



These soils are very poor conductors, thus little or no current may short circuit into the ground. Because the wire didn't break, it can continue to transmit energy between the converters. This energized wire poses a hazard to any people or animals who happen upon it.

HMI	human-machine interface
hot work	Working on electrical equipment while it is energized.
HVDC	high-voltage direct current. Direct current electricity at a high voltage relative to the surrounding environment.
IEEE	Institute of Electrical and Electronics Engineers
IGBT	insulated gate bipolar transistor
inverter	An electrical device that can convert AC electricity into DC electricity. Strictly speaking, inverters cannot convert DC electricity into AC electricity. However, the terms 'inverter' and 'converter' are often interchanged in common usage.
kHz	kilohertz, or 1,000 hertz
kV	kilovolt, or 1,000 volts
kW	kilowatt, or 1,000 watts. One kW is the power consumed by ten 100-watt incandescent light bulbs.
kWh	kilowatt-hour. The quantity of energy equal to one kilowatt (kW) expended for one hour.
LIDAR	Light Detection and Ranging
litz wire	An electrical wire or cable made of multiple individually insulated strands of wire. Litz wire is used in high frequency AC applications and is designed to reduce power losses caused by skin effects and proximity effects that occur at high frequencies.
monopolar	A direct current circuit that operates one leg of the circuit at an elevated voltage, and the return leg at or near ground voltage. The return leg can use a metallic conductor or, in the case of earth or sea return systems, can use the earth or sea to complete the circuit. An HVDC SWER circuit is one type of monopolar circuit.



MW	megawatt, or 1,000 kilowatts
NEC	National Electric Code
NESC	National Electric Safety Code
PCA	Polarconsult Alaska, Inc.
PCB	printed circuit board
PPS	Princeton Power Systems, Inc.
RMS	root-mean-square. The RMS voltage is the mean absolute voltage over any whole number of waveform oscillations. For a sinusoidal waveform (such as normal AC electricity), the RMS voltage is the peak voltage divided by the square-root of 2. Nominal 120 VAC electricity thus has a peak voltage of about +/-170 volts relative to ground.
sea return	A means of completing an electrical circuit by using the sea (or more generally rivers, lakes, and other water bodies) as a return path instead of a second wire. This approach is frequently used on submarine cables where the cost savings from not installing a second cable justify this approach. Sea return can be used for single-phase AC circuits or for DC circuits.
spur and belt	A common method of climbing utility poles, trees, and similar objects. Special climbing spurs are strapped onto the feet and a large belt is fixed around the climber's waist. The climber loops the belt around the pole and drives the spurs into the pole. The climber then 'walks' up the pole with the spurs, and hitches the belt along the pole for support.
step potential	A voltage gradient that occurs at the ground surface due to earth return currents. If the voltage gradient is high enough, it can pose a hazard to people or wildlife stepping in the vicinity.
SWER	single wire earth return. Another term for an earth return or sea return circuit. The name emphasizes the fact that these types of circuits only require one wire, as compared with two or more wires for other types of circuits.

Transmission-class

Refers to higher-voltage electrical systems. Definitions vary, but systems operating above nominal 35 kV are generally classified as transmission-



class. Most remote Alaska interties function as transmission systems, but are operated at distribution-class voltages.

twisted pair A generic term for communications cable that uses multiple individually insulated wires. Each pair of wires is twisted together, hence the name.

V volt. A unit of electrical potential. Some typical voltages are:

Alkaline battery (AAA, C, D, etc.)	1.5 volts (DC)
Car battery	12 volts (DC)
Household electricity	120 volts (AC RMS)

1.0 INTRODUCTION

1.1 ALASKA'S RURAL ENERGY PROBLEM

Energy costs throughout most of rural Alaska have long been significantly higher than in Alaska's urban areas. In recent years, rural energy costs have escalated dramatically, to the point where they are making life in many villages unsustainable.

For most of Alaska's villages, diesel-electric plants are currently the best solution for power generation. Such plants and the accompanying infrastructure such as bulk fuel facilities are readily adapted to most any locality, and they are omnipresent throughout Bush Alaska.

The economics of diesel electric power plants suffer from the small size and geographic isolation of Alaska's villages. Diesel-electric plants have high capital and operating costs, and they pay a premium for already expensive diesel fuel because of the high transportation and storage costs in these remote areas. Additionally, these plants have firmly hitched rural Alaska's local economies to the increasingly volatile global energy markets. In the summer of 2008, the narrow shipping and delivery windows imposed by seasonal ice and low water conditions in many parts of the state resulted in many villages buying a year's worth of fuel at record high prices.

For many of these communities, alternatives to diesel generation are possible in the form of local energy resources such as hydro, wind, geothermal, tidal, solar, gas, coal, biomass, or other generation technologies based on locally available resources. However, many of these alternatives are extremely costly on a unit basis because of the small size of the villages that could be served. These alternatives frequently lack the economy of scale necessary to reduce their installed costs to a level where they can compete with diesel generation. Also, there are many villages that lack nearby energy resources.

Alaska's electrical utility and support community has long recognized that electrical interties are one logical solution to this problem. Interties can tie villages together and achieve the economies of scale necessary to make alternatives to diesel generation economically viable. By consolidating duplicated small diesel plants and bulk fuel facilities, interties can also lower the costs of diesel generation.

Unfortunately, the current costs for constructing conventional distribution-class alternating current (AC) interties in rural Alaska range from \$140,000 to over \$400,000 per mile. Many rural interties are not cost effective at this price and, as a result, only a few have been built.

A lower-cost electrical transmission system would benefit many Alaska villages by enabling them to combine their loads and achieve the economies of scale necessary to make local energy resources competitive with diesel generation. A lower-cost transmission system would also enable these villages to justify reaching farther out to tap nearby local renewable energy resources.

1.2 HVDC TRANSMISSION INTERTIES AS A SOLUTION

The high cost of rural AC interties can be attributed to many factors. Two significant cost contributors common to many remote intertie projects are logistics and foundations. Replacing the complex three- or four-wire intertie required for AC with a single wire system enables significant materials reduction and lessens foundation loads, bringing these costs down. With so many wires aloft, the support structures become more complex, having to support the multiple wires, maintain wire-to-wire separations, handle torsion, and so on. The resulting intertie usually has short spans, typically around 300 feet. This results in a lot of poles, a lot of hardware, a lot of wire, and a lot of foundations. When the logistics, shipping costs, soil conditions, working conditions, and environmental loadings typical in Alaska are considered, this type of intertie often becomes extremely expensive.

Monopolar high-voltage direct current (HVDC) electrical transmission utilizing a single wire earth return (SWER) circuit needs only a single wire, eliminating all of the design issues resulting from the multiple wires of an AC system. By using a single wire, dramatic simplifications in the transmission line design are possible, which can translate to dramatic cost savings compared to a three-phase AC line.

Another advantage of HVDC transmission is the ability to use cables over long distances. HVDC SWER or monopolar HVDC using a single cable can connect villages separated by lakes, bays, fjords, or lands where overhead transmission is not practical, cost effective, or desirable.

In areas where direct-current SWER circuits are not appropriate, two-wire monopolar HVDC lines can also achieve cost savings relative to conventional AC interties, although the savings will be less than for the HVDC SWER transmission concept. Bipolar HVDC interties can also offer advantages, although the additional costs of the extra converters and second transmission line would bring the cost of a bipolar HVDC system back into the range of existing AC interties.

HVDC power transmission also presents other advantages over AC power transmission. These advantages include:

- Asynchronous connection
- Ability to use buried or submarine cables for long distances



1.3 THIS HVDC PROJECT

Commercial HVDC transmission technology has been available for over 50 years, but it is limited to large scale power transmission of 100s or 1,000s of megawatts (MWs). Such systems are far too large for remote Alaska's transmission needs, which are typically 100s to 1,000s of kilowatts (kW). No commercially available utility-grade HVDC conversion technology currently exists that is suitable for remote Alaska applications.

Polarconsult has worked with Alaska Village Electric Cooperative, Inc. (AVEC) and the Denali Commission to define a three-part development effort to prepare a small-scale HVDC transmission technology for commercial deployment in the Alaska market. This phased development approach has been adopted to enable early identification of any problems or limitations of the HVDC technology, thereby minimizing the sunk costs of this development effort should a critical limitation of the technology be identified.

The three-part development effort is organized as follows:

Phase I - Preliminary Design and Feasibility Analysis (current project)

Phase I evaluated the technical and economic feasibility of the proposed HVDC system. This included defining the technical design parameters for the system, defining design considerations for the transmission and converter systems, and estimating probable costs for these systems. For the converter technology, Phase I included initial prototyping and successful testing of the converter technology.

Phase II - Prototyping and Field Testing

Phase II will see the construction and testing of fully functional prototypes of the transmission and converter systems. This effort will validate the design of these systems and will also validate the efficiencies and feasibility of the construction methods necessary to make the system a success on remote Alaska applications. The experience gained in Phase II testing will be used to develop and refine construction methods and cost estimates and to refine the economic analysis of the technology.

Phase III – Demonstration Project

Phase III will see the design, permitting, construction, and operation of a functioning HVDC intertie between two Alaska villages. The Phase III demonstration project location will be selected during Phase II of the project.

This report is the final deliverable of Phase I of the HVDC development effort.



1.4 LIMITATIONS OF PHASE I DELIVERABLES

This Phase I effort establishes generalized design criteria that are representative of applications in remote Alaska. The primary intent of establishing these criteria and designs is to enable the Phase I preliminary design and feasibility analysis of the HVDC system to be completed. The design criteria is set forth in this document to provide a clear understanding of the conditions and assumptions used to complete Phase I tasks and to assure that the findings from these Phase I activities will provide meaningful guidance for continuing development efforts for the proposed HVDC system.

The design criteria set forth in this document are in no way intended to represent conditions on or be used for design of any specific project. Unique design conditions may exist on any specific transmission system that differ from the conditions stated in this report. All design conditions must be considered by the design professional and, where appropriate, the generalized design criteria set forth herein must be validated and adjusted to satisfactorily meet those specific conditions. The authors assume no responsibility for actions arising from inappropriate use of the conceptual design criteria or conceptual designs presented in this report.



2.0 A PRIMER ON HVDC TECHNOLOGY AND SWER APPLICATIONS

2.1 THE HISTORY OF HVDC

2.1.1 1880s: The Age of Electricity Begins with Direct Current

The first utility-scale application of electricity was pioneered by Thomas Edison in New York City. Edison Electric Light Company designed and built the Pearl Street Station in lower Manhattan, which began delivering electrical energy to customers in the surrounding blocks in 1882. This electrical utility provided about 600 kilowatts of direct current (DC) electricity to about one square mile of New York City, mainly for lighting ¹.

1880s technology did not provide an economical way for Edison's enterprise to scale to a viable city-wide business. DC was not readily stepped up to higher voltages, requiring ever-larger cables or ever-higher losses to move useful amounts of electricity to potential customers.

A competing electrical technology, alternating current (AC) electricity invented by Nikola Tesla and commercialized by George Westinghouse, was well suited to stepping up voltages, making electricity transmission across town and between cities economical.

AC electricity quickly prevailed over Edison's DC system. By the 1890s, AC electricity was the industry standard.

2.1.2 1950s: HVDC Becomes Commercially Viable

In the 1950s, technological advances enabled DC systems to reenter the electric utility industry. With the commercialization of the mercury arc-valve, voltage transformation of DC and conversion between DC and AC electricity on a large scale became cost-effective. This allowed utilities to begin using high-voltage direct current (HVDC) transmission links in their systems.

Because of the large footprint and high capital cost of these early HVDC converters, utility usage of HVDC remained limited to transmission functions. AC remained the industry standard for electricity generation, distribution, and consumption.

¹ http://www.ieeehgn.org/wiki/index.php/Pearl_Street_Station





Figure 2-1: Typical Large HVDC Station

2.1.3 HVDC Today

Today, HVDC converter technology has advanced to use high efficiency solid state hardware, and HVDC links are utilized for electrical transmission throughout the world. While the technology has advanced considerably since the 1950s, utility application of HVDC remains limited to transmission functions. The smallest utility-grade HVDC systems are designed to transmit 10s or 100s of megawatts ². Some notable HVDC installations include:

- Swedish Mainland to Gotland Island: 20 MW, 100 kV, monopolar submarine cable with sea return. Commissioned in 1956, this was one of the first HVDC interties installed in the world. This original system was decommissioned in 1987 ³.
- Pacific Intertie – Celilo, Oregon to Sylmar, California: 846-mile, 3,100 MW, 500 kV, bipolar overhead line. Commissioned 1970.
- British Columbia Mainland to Vancouver Island, Canada: 45-mile, 682 MW, 260-280 kV, bipolar submarine and overhead system. The first pole was commissioned in 1968, and a second pole was commissioned in 1977 ⁴.

² “HVDC Lite,” distributed by ABB, is one example of the smaller utility-grade HVDC systems.

³ The original system used on-shore grounding grids to complete the transmission circuit via sea and/or seabed pathways. This first HVDC link was augmented by a second 150 MW monopolar HVDC link to the island in 1983, and a third 150 MW monopolar link in 1987. Today, these two newer circuits are operated together as a bipolar transmission link.

⁴ The first monopolar line is rated for 312 MW at 260 kV, and the second monopolar line is rated at 370 MW at 280 kV.



- Nelson River Bipolar System, Nelson River Hydro Complex to Southern Manitoba, Canada: Two bipolar transmission systems operate between the hydropower projects along the Nelson River in northern Manitoba and Winnipeg. The first system is a 540-mile, 1,620 MW, 450 kV overhead bipolar circuit commissioned in 1977. The second is a 560-mile, 1,800 MW, 500 kV overhead bipolar circuit commissioned in stages between 1978 and 1985. Notably, both systems traverse permafrost terrain similar to that found in Alaska, and can operate in SWER mode, moving 1,000s of amperes of current through earth-return ⁵.
- Cross-Sound Cable, New Haven, CT to Long Island, NY: 24-mile, 330 MW, 150 kV bipolar submarine cable. Commissioned in 2002, this cable uses ABB's HVDC Light technology. Both HVDC conductors and a fiber optic telecommunications cable are bundled into a single cable to simplify installation ⁶.
- England – France Cross Channel Intertie: 38-mile, 160 MW, 100 kV bipolar submarine cable. The original system was commissioned in 1961, and replaced in 1986 by a larger system operating at 270 kV and 2,000 MW capacity. A bipolar system was originally installed to reduce magnetic anomalies that could interfere with shipping.
- Sardinia – Corsica – Italian Mainland, Italy: 500 MW, 200 kV both earth and sea returns. The first 200 MW pole of this system was commissioned in 1965. A second 300 MW pole was installed in 1992. This system is unusual because it is a multipoint system (serving three load centers), unlike most HVDC interties which transmit power between only two points.
- Five HVDC systems ⁷ interconnect the Texas grid and U.S. electric grid in neighboring states. Most of these stations were commissioned in the 1980s. Because of these stations, Texas has an asynchronous grid connection to the remainder of the Lower 48.
- Three Gorges Dam to Shanghai, China: 530-mile, 3,000 MW, 500 kV, bipolar overhead line. A total of four HVDC lines are planned between Three Gorges and China's eastern coastal regions. The first bipolar circuit was commissioned in 2003 and the second in 2006.
- Victoria to Tasmania, Australia: 500 MW, 400 kV, monopolar submarine cable with sea return. Commissioned in 2005.

⁵ http://www.hydro.mb.ca/corporate/facilities/ts_nelson.shtml

⁶ Cross Sound Cable Connector Project Literature, www.abb.com

⁷ The five HVDC systems are the 220-MW back-to-back North DC Tie, 600-MW back-to-back East DC Tie, 36 MVA back-to-back EGPS DC Tie, 150 MVA back-to-back RAIL DC Tie, and 80 MVA Laredo variable frequency transformer (VFT) Tie. (www.ercot.com).



- Sweden to Germany, Baltic Cable: 600 MW, 450 kV, with earth return via deep hole electrodes. Commissioned 1993.

2.1.4 Technical Considerations of HVDC

HVDC links can be superior to high voltage AC links for several key reasons:

- HVDC links are less costly and/or more efficient than AC links under certain circumstances.
- Long interties utilizing insulated cables (as for submarine applications) are possible with HVDC electricity, but prohibitively difficult with AC electricity due to cable capacitance and reactive power losses.
- HVDC links provide an asynchronous connection between AC electrical grids. Analogous to a clutch on a mechanical system, an HVDC intertie allows each AC system to operate at its own phase and frequency and still allow power transfer between the systems. This increases the stability of both AC grids.
- For a given power transfer requirement, HVDC interties can require less right-of-way than comparable AC interties. They can also have a variety of other regulatory, permitting, or environmental advantages compared to AC interties.

Because of the high cost of the converter systems necessary to convert HVDC to a more readily used AC waveform, HVDC is generally limited to transmission applications. Accordingly, most or all utility HVDC systems in use today are point-to-point transmission lines, with no intermediate take-off points or sub-stations for communities en route.

In the case of a small-scale remote Alaska HVDC application, there is still an economic barrier to installing an intermediate take-off point, but this barrier is measured in the \$100,000s. A remote lodge or fish camp likely can't justify the cost to tap the HVDC line, but most villages can.

As HVDC interties are considered for remote Alaska applications, utilities may desire to extend AC distribution as an underbuild or overbuild on an overhead HVDC line. Similarly, other utilities may desire to utilize the overhead structures to co-locate their cables. This practice is possible so long as applicable code requirements and safety provisions are followed. It may be desirable to use conventional construction in the immediate vicinity of villages to facilitate co-location of multiple utility cables, transitioning to a different, optimized overhead structure for HVDC once away from the village.



2.2 SINGLE WIRE EARTH RETURN (SWER) CIRCUITS

2.2.1 Definition of SWER

In its simplest form, an electrical circuit requires two current pathways, typically wires. One wire goes from the power supply to the load, and a second wire goes from the load back to the power supply. Both single-phase AC and DC circuits rely on this basic configuration. The wire from the power supply to the load is usually at an increased voltage relative to ground, and so it is insulated for safety and to prevent short circuits. The wire from the load back to the power supply is usually at a much lower voltage relative to ground and thus is usually but not always insulated.

In Single Wire Earth Return (SWER) circuits, the wire that serves as the second current pathway from the load back to the power supply is replaced with a suitable, convenient, and safe current pathway. In the most general case, this 'non-wire' pathway can be a car or truck chassis, the metal handle of a flashlight, the earth, natural water bodies, or other objects that can safely complete the electrical circuit.

Sea return circuits are similar to earth return circuits. The only difference is that the sea, or any water body, is used as the predominant return circuit pathway. Parallel pathways, such as the seabed, are also available for current flow.

2.2.2 Why use SWER?

The primary advantages offered by SWER circuits include:

- Lower costs (eliminate the second conductor).
- Higher efficiency (lower electrical losses).
- Increased reliability (the earth does not break very often).

The primary concerns associated with SWER circuits include:

- Avoiding corrosion of buried or submarine metallic objects in the vicinity of the SWER circuit.
- As with all electrical systems, safety.

SWER circuits are widely used for utility transmission and distribution of electricity all over the world. Numerous HVDC interties are SWER circuits, consisting of a single high voltage cable and an earth or sea return to complete the transmission circuit. Many of these are installed in climates and conditions similar to Alaska, notably in Scandinavia. In many nations, single phase AC SWER circuits are accepted practice and are industry standard for serving rural areas.



Nations and jurisdictions that use SWER AC circuits to economically serve their rural areas include the following^{8, 9}.

- Australia (over 100,000 miles in service)
- Cambodia (Electricite' du Cambodge)
- New Zealand
- Vietnam
- Laos (Electricite' du Laos)
- South Africa (Eskom Distribution)
- Saskatchewan
- India
- India
- Brazil

2.2.3 History of SWER in Alaska

At least two single-phase AC SWER circuits have been successfully built and operated in Alaska. These AC SWER circuits demonstrate that SWER is a proven, beneficial, and appropriate technology for rural Alaska transmission applications.

2.2.3.1 Bethel – Napakiak AC-SWER Line

In 1981, a 10.5-mile 14.4 kV single-phase AC SWER line was constructed to connect the small village of Napakiak to the City of Bethel. This line used bipod structures to suspend a 7#8 alumoweld conductor.

This line was constructed at a cost of \$23,000 per mile (1980 \$) and operated successfully for many years. Arguably, the line had two shortcomings, neither related to its SWER operation: (1) the structural design of the line relied upon the conductor to provide longitudinal support to the bipod poles between dead-ends, and on at least one occasion a conductor break cause a series of structures to fall down, and (2) over time, the load in Napakiak exceeded the line's capacity. However, the line was an unqualified success at demonstrating that SWER can reduce the costs of power transmission in rural Alaska.

⁸ "Single Wire Earth Return for Remote Rural Distribution, Reducing Cost and Improving Reliability." Conrad W. Holland. Maunsell Ltd., An AECOM Company.

⁹ "Single Wire Power in Alaska." State of Alaska, Division of Energy and Power Development. R.W. Rutherford Associates. 1982.



Common misperceptions about this line have given it a negative reputation, which is often incorrectly attributed to its 'innovative' SWER design. The line did suffer high losses, but these can be attributed to unmetered loads in Napakiak and the poor condition of the distribution system in Napakiak.

The Alaska Energy Authority plans to reconstruct the Bethel-Napakiak line to a conventional three-phase line. Budgeted costs for this upgrade are \$264,000 per mile, about five times higher than the inflation-adjusted cost of the original line ¹⁰.

2.2.3.2 Kobuk – Shungnak AC-SWER Line

A 10-mile single-phase AC SWER line was constructed to connect the village of Shungnak to Kobuk in northwestern Alaska. The line and the SWER system worked successfully; however, the support structures were constructed of local spruce trees, and eventually the bases rotted. Like the Bethel – Napakiak SWER line, this line also successfully demonstrated SWER viability in permafrost regions. In 1991, this 10-mile line was replaced with a conventional three-phase 7.2/12.4 kV AC line with poles attached to driven steel H-piles at a cost of \$1.1 million, or about \$110,000 per mile in 1991 dollars ¹¹.

2.2.4 Future of SWER in Alaska

The transition of most Alaska villages to three-phase distribution systems has diminished the value of single-phase AC SWER interties. AC phase converters would be necessary to interface the intertie with one or both village grids. Also, the national electrical codes adopted by the State of Alaska do not allow the use of SWER circuits for routine power transmission or distribution. Perhaps because of these factors, there is currently a general lack of interest in SWER technology in Alaska.

Despite such factors, SWER circuits remain a proven and cost-effective option for remote Alaska applications, and they warrant serious consideration. Coupled with HVDC, SWER offers cost and technical advantages that have the potential to revolutionize remote power transmission in Alaska.

Affordable energy is a vital underpinning of creating a sustainable economic base for Alaska's remote areas. Affordable transmission is key to achieving affordable energy, and the coupling of SWER and HVDC presents the brightest opportunity for achieving

¹⁰ Alaska Energy Authority. FY 2008 Capital Project Summary Sheet, Napakiak-Bethel Intertie Right-of-Way and Site Control Project. April 19, 2007.

¹¹ Petrie, Brent. Alaska Village Electric Cooperative, Inc. Personal Communication. February 2008.



affordable transmission in Alaska. Accordingly, the future of SWER in Alaska is very promising.

2.3 HVDC FOR ALASKA

The list of existing HVDC projects in section 2.1.3 illustrates the fact that today's commercial HVDC technology remains limited to large scale transfer of electricity, normally measured in the 100s or 1,000s of megawatts. Such technology has very limited application in Alaska, as our largest grid, along the railbelt, has a peak load of well under 1,000 MW. Most remote loads are measured in the 100s of kW.

The lack of commercial HVDC technology in the kilowatt class appropriate for remote Alaska applications means that the numerous benefits offered by HVDC transmission are not presently available to Alaska's remote communities. The key objective and impetus for this project is to lower the cost of remote Alaska interties by extending the reach of commercially available HVDC technology down to the kilowatt class needed to serve Alaska's remote energy transmission needs.

The applications for this technology in Alaska are numerous and include:

- Connecting Bethel and nearby villages with a wind farm along the Bering Sea coast.
- Connecting villages along the Yukon River such as Koyukuk, Nulato, Ruby, and Kaltag with the proposed Toshiba nuclear battery in Galena.
- Connecting 25 southwestern communities to a proposed 25-MW geothermal plant near King Salmon.
- Connecting North Slope communities such as Atqasuk with Barrow to share in the low-cost electricity derived from Barrow's gas fields.
- Developing the geothermal resource at Pilgrim Hot Springs and transmit the power to Nome via HVDC intertie.
- Completing connections in the Southeast Intertie via an affordable HVDC submarine cable.



3.0 HVDC – AC CONVERTER

The HVDC – AC converter is the device that interfaces between the HVDC transmission line and a village's three-phase AC electrical system. Two converters would be required for a monopolar HVDC intertie – one converter near each village at the end of the HVDC intertie.

3.1 CONVERTER DESIGN BASIS

This project includes phased development of the converter. In the completed Phase I effort, a 'demonstrator' was designed, constructed, and tested to confirm the technical and economic feasibility of the converter technology. In later phases of the project, development efforts will focus on a fully functional one-MW converter. The Phase I demonstrator contains subassembly designs and components that will be directly used in the full-scale converter design. Specifications for the Phase I demonstrator device and the fully functional one-MW converter are included in Appendix A. Key highlights of the full scale converter are discussed below.

3.1.1 Power Throughput

Based upon discussions with Alaska Village Electric Cooperative, Inc. (AVEC) and review of the range of electrical loads characteristic of remote Alaska communities, the nominal power throughput of the HVDC converter is one megawatt (MW). This power throughput will be used as the basis for all feasibility, design, and economic analyses.

The converter technology is scalable to commercial units in the range of approximately 100 kW to five MW. Units beyond this range are also viable, but additional development would be necessary to optimize components and designs for higher power throughput.

3.1.2 Direct Current Operating Voltage

The DC operating voltage is 50,000 volts. This is the nominal DC input/output voltage of the converters and is also therefore the nominal voltage of the transmission line between converters. This voltage optimizes cost and performance considerations of both the transmission line and the converter modules.

3.1.3 Alternating Current Interface Voltage

The converters interface with 60 hertz, three phase 480 VAC power. The nature of the converter design allows for considerable deviation from this specification as AC input or output.



3.1.4 Design Functionality

The HVDC converters will be designed to be fully automatic and highly redundant to allow for maximum reliability. The one-MW converter will consist of two parallel 500 kW converters, allowing for complete single-part redundancy. In the event that a component failure takes down one of the two internal converters, the second can remain in service at full voltage and ½ power throughput.

When components fail, they are designed to fail-safe. Depending on the failed component, the converter may continue limited operation, or it will cease operations to protect itself and report the failure so corrective action may be taken. All components are designed in a modularized fashion to facilitate rapid on-site repair. The converter modules will be small and light enough that they can be shipped by air or barge, using aircraft and barge services generally available throughout Alaska. All replacement components can be shipped by air, e.g., in a Cessna 206 or similar small aircraft.

3.1.5 Electrical Codes and Approvals

The final converter will be compliant with the National Electric Safety Code (NESC), which is specific to power generation and transmission applications.

3.1.6 Converter Siting and Installation

Converter siting is a project-specific issue and will vary for each installation. The converter is capable of accommodating a wide variety of installation sites, allowing for flexibility in determining the optimal installation site for a given application. Generally, it is anticipated that the converter will be installed in one of the two generalized locations:

- At the village powerplant. In this configuration, the converter would be connected onto the 480 VAC powerplant bus and would feed power to or from this bus depending on operational mode. This would be a typical installation for a generating village, in which case the converter would be taking power from the bus and feeding it to the receiving village via the HVDC intertie. Depending on available space within a given powerplant, the physical converter and appurtenances could be located inside the powerplant or in a prefab enclosure outside and adjacent to the powerhouse.
- At a convenient point on the village's three-phase power grid. In this configuration, the converter would be co-located with an AC transformer to step down village grid voltage (typically 7.2/12.4 kV) to 480 V. The converter and appurtenances would be housed in a small prefab enclosure. This would be a typical installation for a receiving village. Some reasons for installing the converter out on the village distribution system include:



3.0 *HVDC – AC Converter Technology Development*

- Reducing the need to install HVDC lines or cables through the village.
- Locating the HVDC converter closer to soils that are suitable for an earth return grounding system.
- Reducing the length of the HVDC intertie in villages with an extensive three phase AC grid.
- Greater flexibility in siting to address property or related issues.



3.2 PHASE I DEMONSTRATOR DESIGN

Princeton Power Systems, Inc. (PPS) was responsible for development, construction, and testing of the power converter equipment.

The Phase I demonstrator device is a scaled-down bench top implementation of a fully functional bi-directional HVDC converter. The operating voltage and power throughput of the demonstrator were each reduced by approximately $\frac{1}{4}$ to achieve cost savings on this phase of the project. The one-MW converter will be comprised of multiple demonstrator subassemblies to increase the operating current and voltage to achieve the higher power throughput.

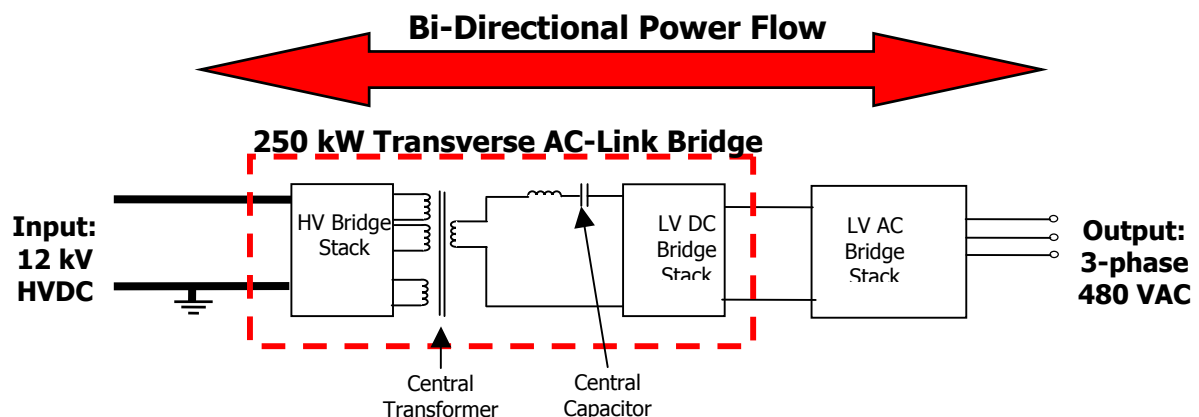
The demonstrator is designed for bi-directional power flow between three-phase 480 VAC and 12 kV DC. Rated power throughput is 250 kW. More detailed specifications on the demonstrator are included in Appendix A.

3.2.1 Demonstrator Electrical Design

The demonstrator is capable of bi-directional power conversion between 12 kV DC and 3-phase 480 VAC up to 250 kW. The demonstrator design is scalable to one MW at 50 kV by 'stacking' multiple subassemblies of the demonstrator to increase the DC voltage and total power throughput. The demonstrator is comprised of four major assemblies, indicated schematically in Figure 3-1 and listed below. These assemblies and their function are described on the following pages.

- High-Voltage Direct Current Bridge Stack
- Central Transformer / Central Capacitor
- Low-Voltage Direct Current Bridge Stack
- Low-Voltage Alternating Current Bridge Stack

Figure 3-1: Schematic Electrical Representation of Demonstrator Unit



3.2.1.1 Principles of Operation

Principles of operation are the same for both the demonstrator and the full converter.

In converter mode (HVDC to AC power conversion), the high voltage bridge stack takes in the 12 kV DC across the 10 stage boards, so each board 'sees' approximately 1200 V DC. These boards use insulated gate bipolar transistor (IGBT) switches to 'chop' this incoming HVDC energy into small energy packets. These packets form a dynamic waveform (similar to an AC waveform) that is fed into the central transformer / central capacitor, where they are stepped down from 12 kV to 700 V. This 700 V power is then fed through the low voltage DC bridge stack to the low voltage AC bridge stack, which constructs a three-phase 480 VAC output from the energy packets.

In inverter mode (AC to HVDC power conversion), energy enters from the three-phase 480 VAC side. The low voltage AC bridge stack converts this to 700 V DC. The 700 V DC is fed to the low voltage DC bridge stack, which 'chops' the incoming energy into packets, forming a dynamic waveform (again, similar to an AC waveform) that is fed into the primary side of the central transformer / central capacitor circuit. The transformer steps up the voltage of this waveform from 700 V to 12 kV. Again, the 12 kV is distributed equally across the 10 high voltage stage boards. The high voltage DC bridge stack now reconstructs these high voltage energy packets into the 12 kV DC output.

The major assemblies of the demonstrator are described in the following sections.

3.2.1.2 HVDC Bridge Stack

The HVDC Bridge Stack is comprised of several HV stage boards that interface between the HVDC terminals and the central transformer. Each stage board is a seven-layer printed circuit board (PCB) containing the power circuits and control circuits. Each board receives an isolated power supply to drive the IGBTs, which construct/deconstruct the waveforms between the HVDC terminals and the transformer. Each board also contains an optically isolated control interface used to control the stage board in concert with the overall demonstrator's function.

Each stage board operates on a different voltage plane, so the total DC voltage across the boards is the desired input/output HVDC voltage. For the demonstrator, 10 stage boards are operated at 1,200 volts each to achieve the 12 kV DC voltage.

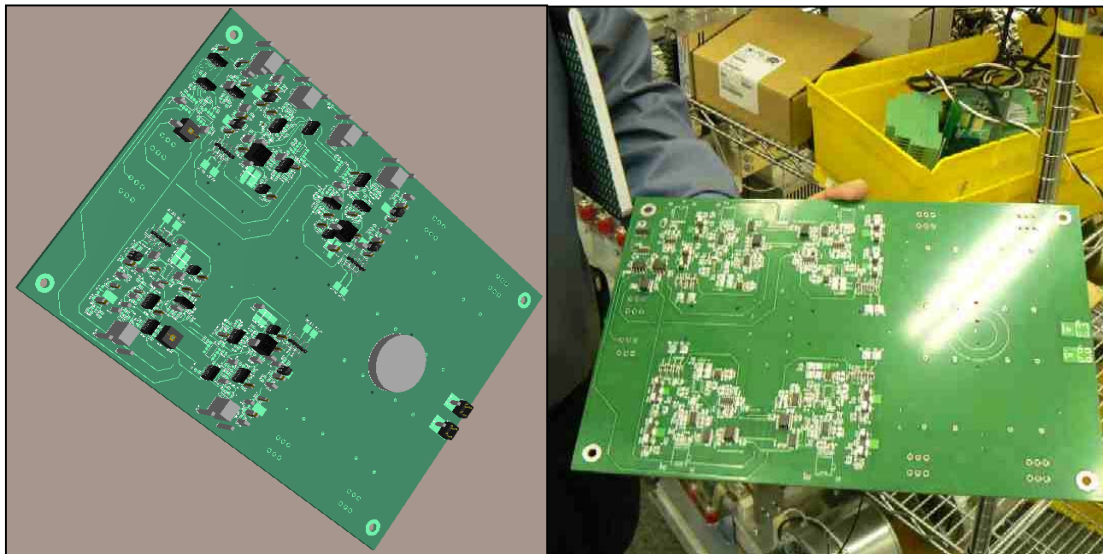
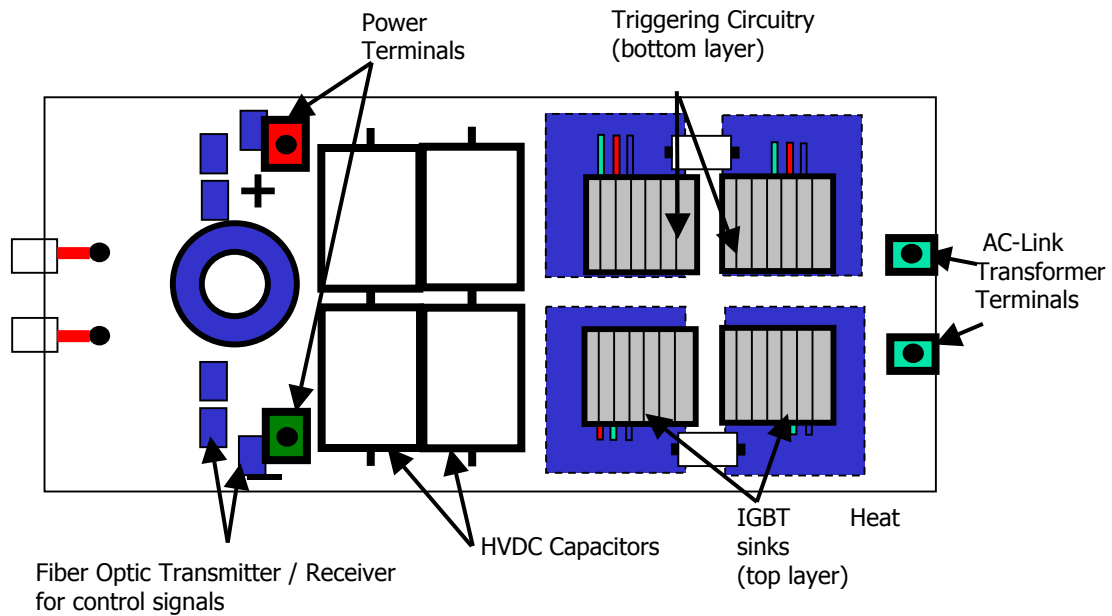


Figure 3-2: Concept Block Diagram of Stage Board (top), Design Model of Stage Board (left), and Manufactured Stage Board (right)

3.2.1.3 Central Transformer / Central Capacitor

The central transformer is a special high-frequency, high-efficiency transformer designed for this specific application. At the transformer's high operating frequency of 6 to 8 kHz, special materials such as a nano-crystalline iron core and litz wire in the primary and secondary windings are necessary to reduce power losses. Losses would be significant without the use of these materials. The transformer converts 700 volts on the primary to 12 kV on the secondary across the ten secondary taps (1,200 volts per tap).

The central capacitor is a capacitor bank that stores energy packets moving between the central transformer and the Low Voltage DC Bridge Stack.

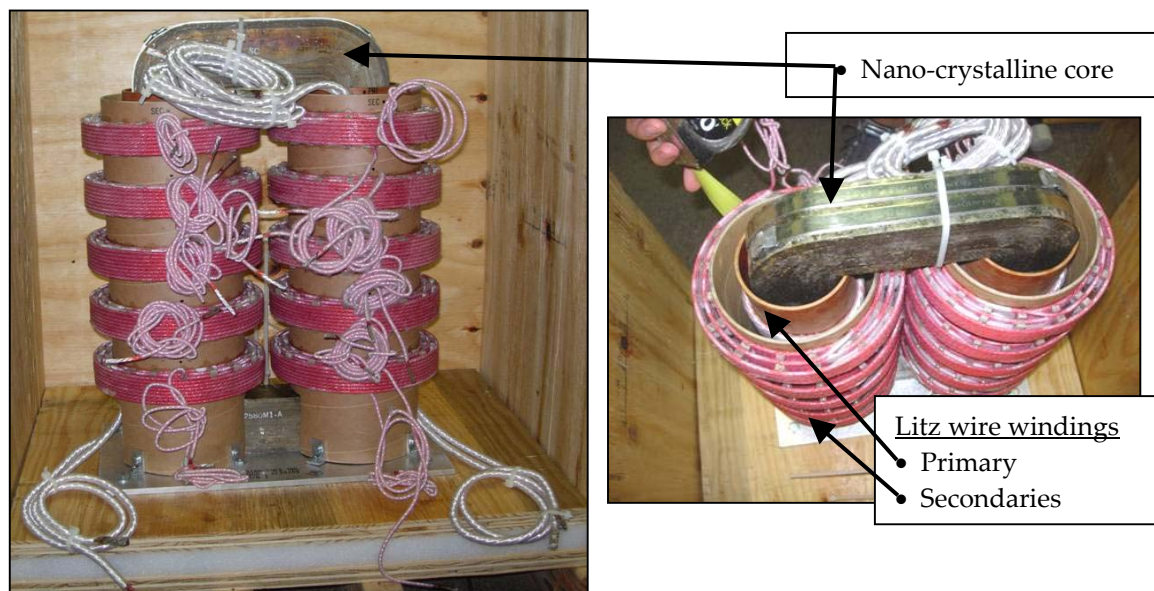


Figure 3-3: High Voltage High Frequency Central Transformer

3.2.1.4 Low Voltage Direct Current Bridge Stack

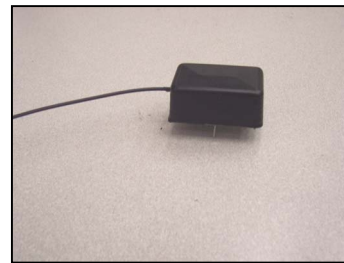
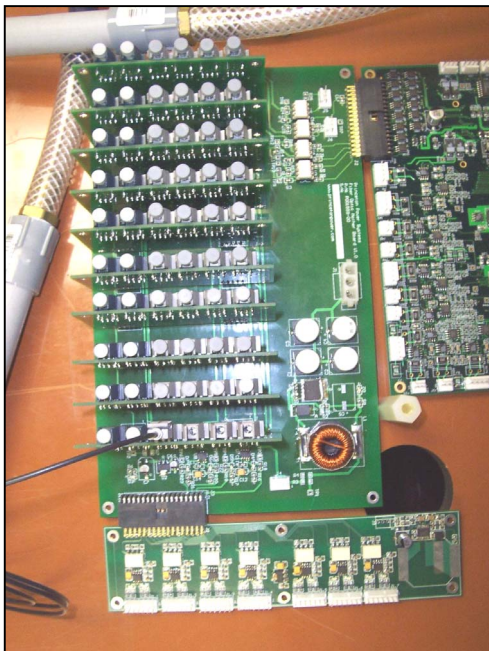
The low voltage DC bridge stack interfaces between the central transformer and the low voltage AC bridge stack. Its function is similar to that of the high voltage DC stack. Namely, it constructs / deconstructs the DC waveforms between the transformer and AC sides of the device.

3.2.1.5 Low Voltage Alternating Current Bridge Stack

The low voltage AC bridge stack is a commercial device manufactured by Semikron. It converts between nominal 700 V DC and three-phase 480 VAC.

3.2.1.6 Controls

Control of the demonstrator circuitry is performed by a separate controller board. This board interfaces with the high voltage stage boards via fiber optics to maintain electrical isolation. Figure 3-4 shows the fiber optic mother board and trigger cards used to achieve this communications link. Because the stage boards are immersed in oil for electric isolation and cooling, oil-proof fiber optic hardware is used.



Single oil-proof fiber optic transceiver

Fiber Optic Mother Board and Trigger Cards.
Controller Board is at right of figure.

Note single fiber optic lead installed at lower left.

Figure 3-4: Fiber Optic Mother Board and Trigger Cards

3.2.2 Demonstrator Mechanical Design

The demonstrator unit is a bench-top prototype. As such, its mechanical design is not suitable for commercial service. However, commercial packaging was factored into mechanical design of the demonstrator. A full one-MW converter based upon the demonstrator design will consist of two cabinets housing all of the electrical hardware for the system. The first cabinet will house the low-voltage assemblies and human-machine interfaces (HMIs), which include the low voltage DC bridge stack, AC bridge stack, and controllers. This cabinet will be cooled using forced air convection. The second cabinet will be an oil tank housing the high voltage DC bridge stack and the transformer. These assemblies will be immersed in the oil bath to reduce electrical standoffs between the stage boards and also to improve cooling for these components.

Because the oil bath is necessary for operation of the high voltage assemblies, mechanical design of an oil bath cabinet was completed for the demonstrator. This cabinet is similar to the cabinet that would be used for the full one-MW converter.

The oil bath is circulated through a radiator to reject heat from the oil tank. On the production unit, the location and configuration of the oil radiator will be site specific, as the radiator may need to dissipate heat to interior or exterior locations. The high voltage assemblies will be mounted to the lid of the tank. For maintenance, the lid will be hoisted directly above the tank allowing access to the components.

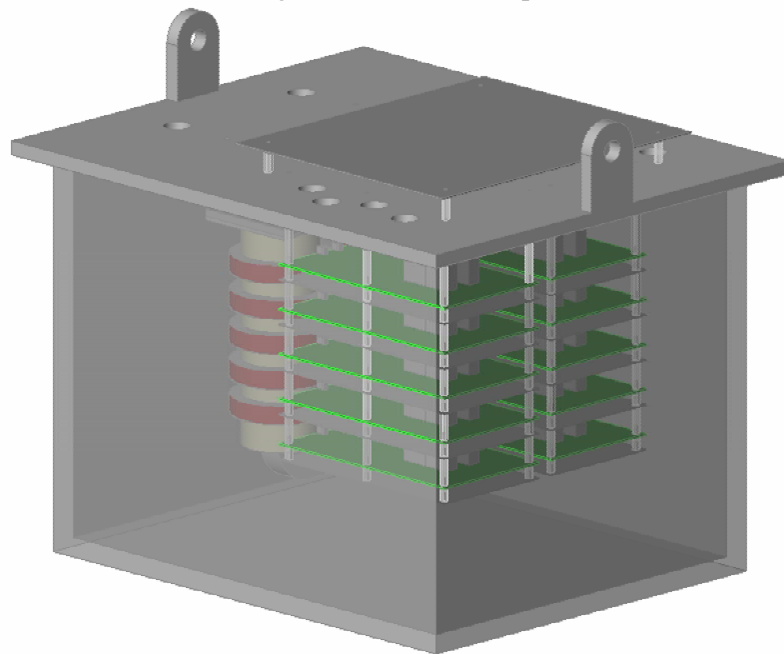


Figure 3-5: Mechanical Design of the Oil Bath Cabinet Showing the Transformer and High Voltage Stage Board Stack

3.2.3 Scaling the Demonstrator Design to the Full Converter Design

The demonstrator is essentially a ¼-scale bench top prototype of the full one-MW HVDC converter. The increased power throughput of the full converter will be achieved by increasing the number of stage boards in the high voltage DC bridge stack to achieve 500 kW at 50 kV DC and by integrating two complete converter assemblies to operate in parallel as a single converter system with one-MW capacity. The same basic electrical and mechanical design concepts employed for the demonstrator will be used for the full converter. This effort will be completed in Phase II of the project.

PPS conducted a preliminary analysis of a converter with an AC interface voltage of 7.2/12.4 kV to directly interface with three-phase village distribution systems. PPS' preliminary finding is that such a converter would have similar cost and electrical efficiency as using a 480V converter coupled with a conventional AC transformer. Given the potential advantages of this configuration, further investigation into this converter configuration would be warranted.

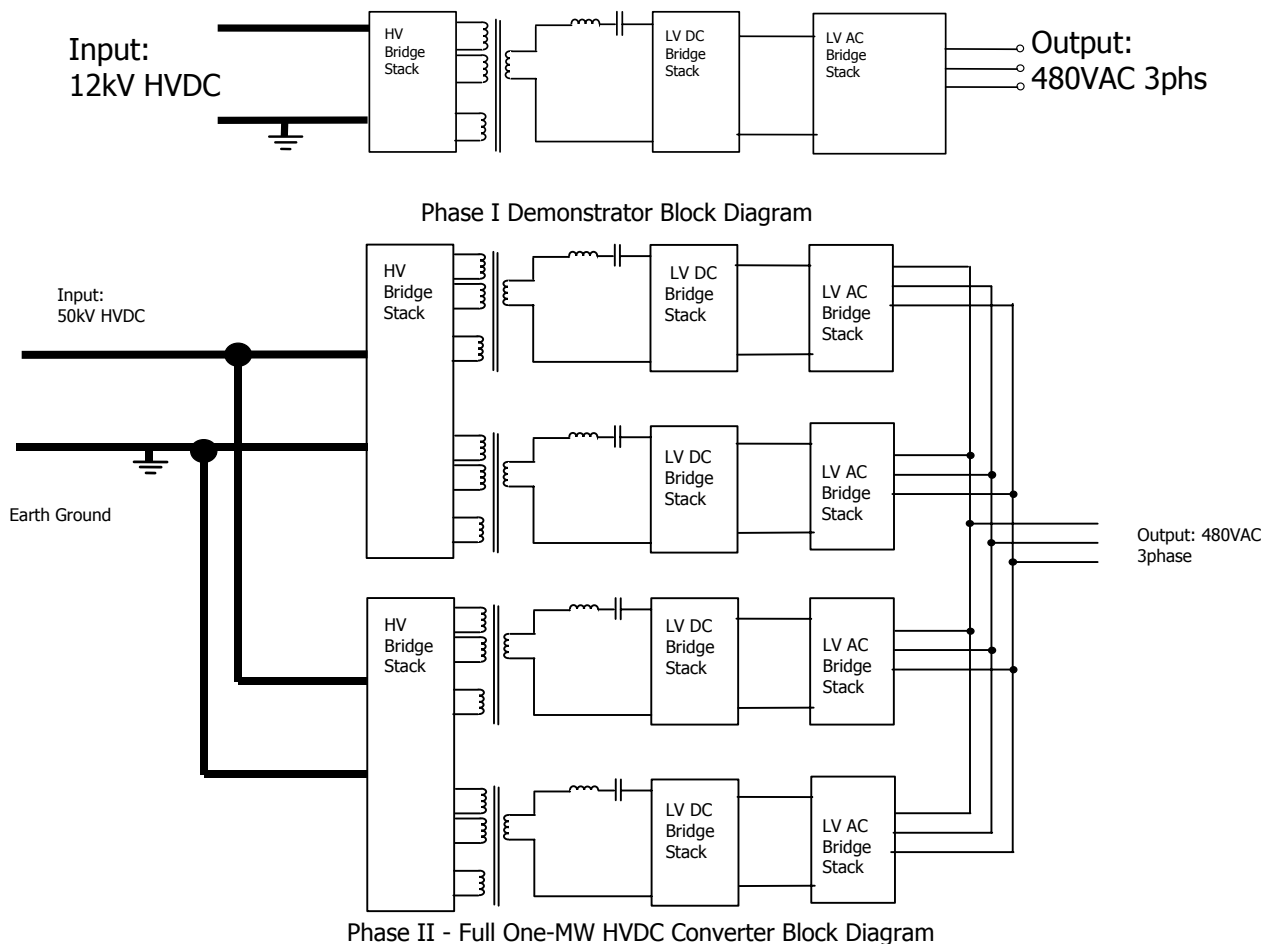


Figure 3-6: Block Diagrams of 250 kW Demonstrator and 1-MW Converter Designs



3.3 DEMONSTRATOR TESTING PROGRAM AND RESULTS

The testing program for the demonstrator had two objectives:

1. Proof of Concept Demonstration
2. Confirmation of System Efficiency

3.3.1 Test Setup

To test the demonstrator, power inputs were needed for both operational modes: AC to HVDC and HVDC to AC. Three-phase 480 VAC was obtained from the local utility service. A 12 kV, 250 kW DC power supply was constructed from three-phase 480 VAC utility service, variacs, two 150 kVA transformers, and rectifiers.

The converter was successfully operated in both rectifier (AC to HVDC) and converter (HVDC to AC) modes.

3.3.2 Demonstrator Efficiency

Demonstrator efficiency is tabulated in Table 3-1 and charted in Figure 3-7. The expected efficiency of the one-MW converter has been estimated based upon demonstrator testing results and the one-MW converter's conceptual design. This is tabulated and charted in Table 3-2 and Figure 3-8, respectively.

3.3.3 Results

Based upon the Phase I efforts, the HVDC converter is considered technically viable, and can be produced at a cost that makes the HVDC transmission system economically viable. System economics are discussed in greater detail in Section 5.



Table 3-1: Efficiency of 250 kW Demonstrator Unit

Power Input (kW)	Input as Percent of Capacity	Total Converter Losses (kW)	Power Output (kW)	Efficiency
2.5	1%	1.3	1.2	46.4%
7.5	3%	1.4	6.1	81.3%
25	10%	1.7	23.4	93.4%
50	20%	2.1	47.9	95.9%
75	30%	2.6	72.3	96.6%
100	40%	3.1	96.9	96.9%
125	50%	3.8	121	97.0%
150	60%	4.5	146	97.0%
187	75%	5.7	181	96.9%
200	80%	6.2	194	96.9%
225	90%	7.1	218	96.8%
250	100%	8.1	242	96.7%

Figure 3-7: Efficiency of 250 kW Demonstrator Unit

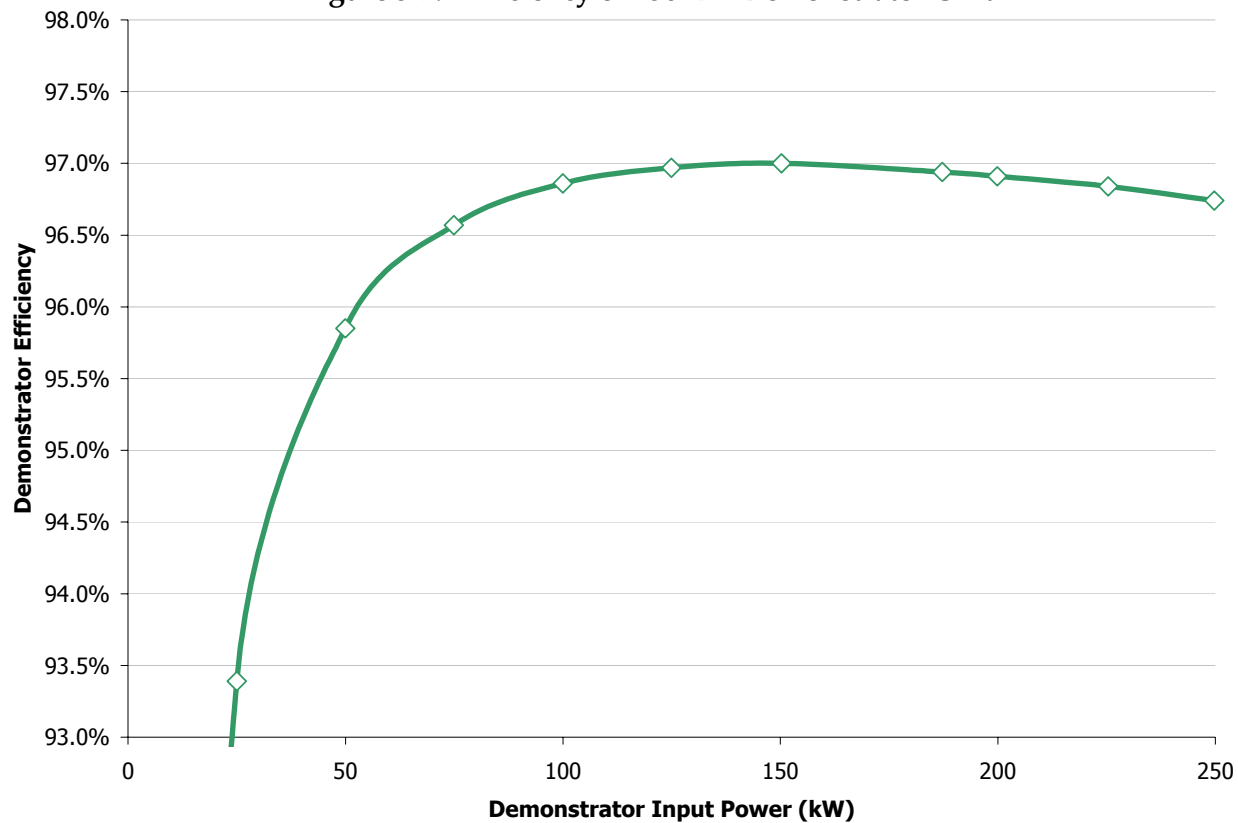
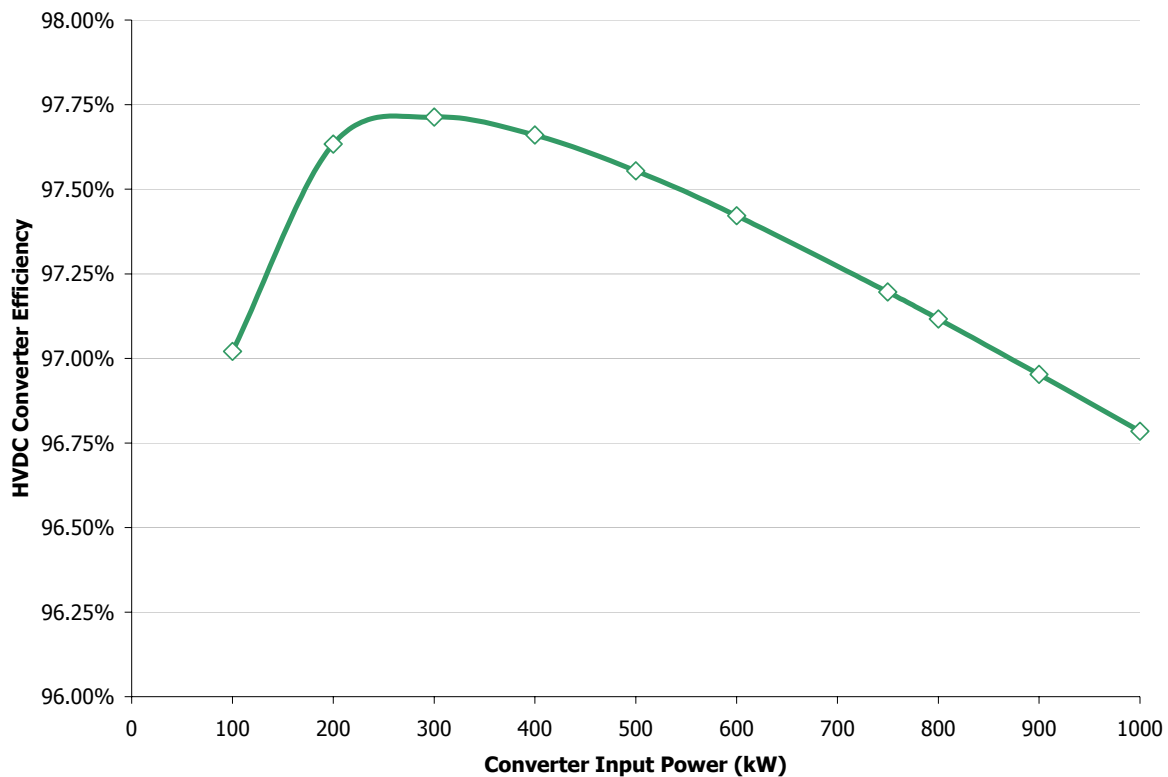


Table 3-2: Projected Efficiency of One-MW HVDC Converter

Power Input (kW)	Input as Percent of Capacity	Projected Converter Losses (kW)	Power Output (kW)	Projected Efficiency
100	10%	3.0	97	97.0%
200	20%	4.7	195	97.6%
300	30%	6.9	293	97.7%
400	40%	9.4	391	97.7%
500	50%	12.2	488	97.6%
600	60%	15.5	585	97.4%
750	75%	21.0	729	97.2%
800	80%	23.1	777	97.1%
900	90%	27.4	873	97.0%
1,000	100%	32.2	968	96.8%

Figure 3-8: Projected Efficiency of One-MW HVDC Converter



3.3.4 Converter Reliability

At this stage in development, the reliability of a commercially manufactured HVDC converter is unknown, but it is expected to be similar to that of comparable commercially manufactured utility-grade electronic power equipment.

It is a given that component failures will eventually occur in the HVDC converters. Accordingly, the HVDC converter design is modularized, which allows for continued operation (with at least 50% power throughput capability) after any single power component failure. When a failure occurs, a new modular component (e.g., a high voltage stack card) can be installed to replace the failed part. This modular design simplifies repairs and also reduces the cost of maintaining a stock of spare inventory parts.

One objective of Phases II and III of this project is to begin establishing a record of HVDC converter and intertie reliability so utilities can justify building HVDC interties. This will mainly occur in Phase III, when converters are installed and operating on a sustained basis in a remote Alaska intertie.



4.0 HVDC TRANSMISSION SYSTEMS

The HVDC transmission intertie can use a monopolar, monopolar SWER, or bipolar circuit, and can consist of overhead wires, buried cables, submarine cables, or a combination of these. Within these general configurations exist endless variations of materials and designs that may be appropriate for any given HVDC system.

This palette of HVDC intertie circuits, constructions, materials, and methods is a part of the transmission engineer's tool box. For any given intertie, the engineer will review the project criteria and use the best tool available for the job. Unfortunately, the transmission engineer's existing tool box has some very expensive solutions for much of Alaska's remote and rugged terrain. The principal objective of this HVDC project is to reduce the cost of remote small power interties. In this regard, the HVDC converter is a means to an end – and the 'end' is a less expensive intertie. Developing intertie designs that are less costly to build than AC interties is thus central to the success of this project.

HVDC power transmission has several important technical differences than AC power transmission. As discussed in this section, these differences can be exploited to reduce the construction costs of remote interties in Alaska. The major differences pertinent to transmission design include:

- Fewer wires. An HVDC intertie can use one, two, or three wires, compared to three or four wires for an AC intertie. For most Alaska HVDC interties, only one or two wires would be necessary.
- Unlimited use of cables. An HVDC intertie can run for practically unlimited distances in buried or submarine cables. AC cable runs are limited to approximately 10 miles without the use of static VAR compensators or similar devices.

This section provides:

1. An overview of the three basic types of HVDC circuits (monopolar, monopolar SWER, and bipolar).
2. An overview of the design considerations and conceptual design values for remote Alaska interties using this HVDC technology.
3. An overview of permitting, regulatory, and code considerations pertinent to HVDC interties.
4. Conceptual control, communications, protection, and safety systems for the intertie.



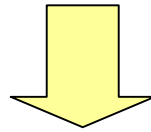
5. Design considerations for HVDC grounding grids.
6. Design considerations for overhead intertie tailored for remote Alaska conditions.
7. Design considerations for buried overland cable tailored for remote Alaska conditions.
8. Design considerations for submarine cable tailored for remote Alaska conditions.



4.1 HVDC CIRCUIT CONFIGURATIONS

At the most abstract level, an electrical circuit requires two current pathways, typically wires. One wire goes from the power supply to the load, and a second wire goes from the load back to the power supply. Both single-phase AC and DC circuits rely on this basic configuration. The wire from the power supply to the load is usually at an increased voltage relative to ground, and so it is insulated for safety and to prevent short circuits. The wire from the load back to the power supply is usually at a much lower voltage relative to ground and is usually but not always insulated. HVDC interties use one of three circuit configurations:

- Monopolar with SWER
- Monopolar with return conductor
- Bipolar



INCREASING COST
AND COMPLEXITY

More complex HVDC circuit configurations normally incorporate elements of the simpler circuits for efficiency, reliability, redundancy and/or safety. For example, all bipolar HVDC systems include earth electrodes and/or a ground conductor so they can operate either pole in monopolar or monopolar SWER mode during maintenance or emergency situations.

Generally, the more complex bipolar circuit configurations are used for large, important interties where the increased reliability, efficiency, and power throughput capability justify the higher cost of these systems.

These three HVDC circuit configurations and their applicability to rural Alaska intertie applications are briefly discussed on the following pages.



4.1.1 Monopolar HVDC Intertie Using SWER

A monopolar HVDC intertie using SWER for the return pathway will generally be the lowest-cost alternative for HVDC power transmission in remote Alaska applications. This circuit configuration will consist of the following major components:

- AC/DC Converter module in the generating village.
- High voltage conductor. This can be an overhead line, buried cable, or submarine cable.
- DC/AC Converter in the receiving village.
- Grounding electrodes in both villages to complete the intertie circuit using earth return.

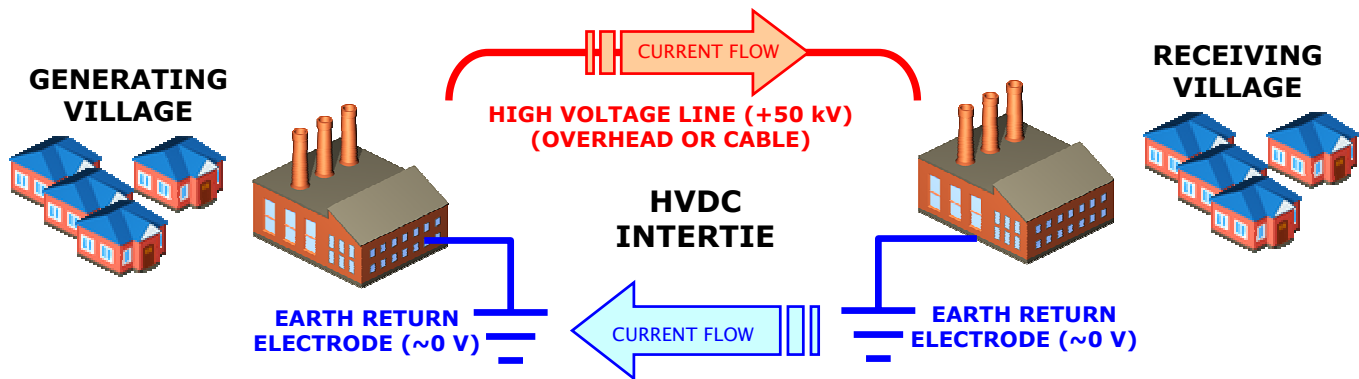


Figure 4-1: Monopolar HVDC Intertie Using SWER

There are numerous examples of monopolar HVDC interties using SWER circuits. The 500-MW submarine HVDC link completed between Victoria and Tasmania, Australia in 2006 is one example of a recently constructed SWER HVDC system.

4.1.2 Monopolar HVDC with Return Conductor

A monopolar HVDC intertie with a return conductor is substantially similar to a monopolar HVDC intertie utilizing SWER. The primary difference is that the earth return is replaced with a dedicated return conductor to minimize earth currents induced by the intertie. Often, such interties will still have the earth electrodes necessary to operate in SWER mode and will operate in SWER mode during maintenance or emergency situations. This HVDC circuit configuration includes the following major components:

- AC/DC Converter module in the generating village.
- High voltage conductor. This can be an overhead line, buried cable, or submarine cable.
- DC/AC Converter in the receiving village.
- Return conductor. This can be an under-built line on the high voltage poles, a separate cable, or incorporated into the same cable as the high voltage conductor, such as a concentric neutral on an AC cable.
- Grounding electrodes in both villages. These will not normally be used to complete the intertie circuit, but they will be used during maintenance or emergencies.

Monopolar return conductors are warranted in areas where a SWER circuit is not viable or desirable. Generally, this is due to the risk of inducing corrosion in buried metallic utilities. The lack of suitable ground conditions for economical earth electrodes would also warrant use of a return conductor. Using an equal-sized return conductor will nearly double the conductor losses relative to a SWER transmission circuit.

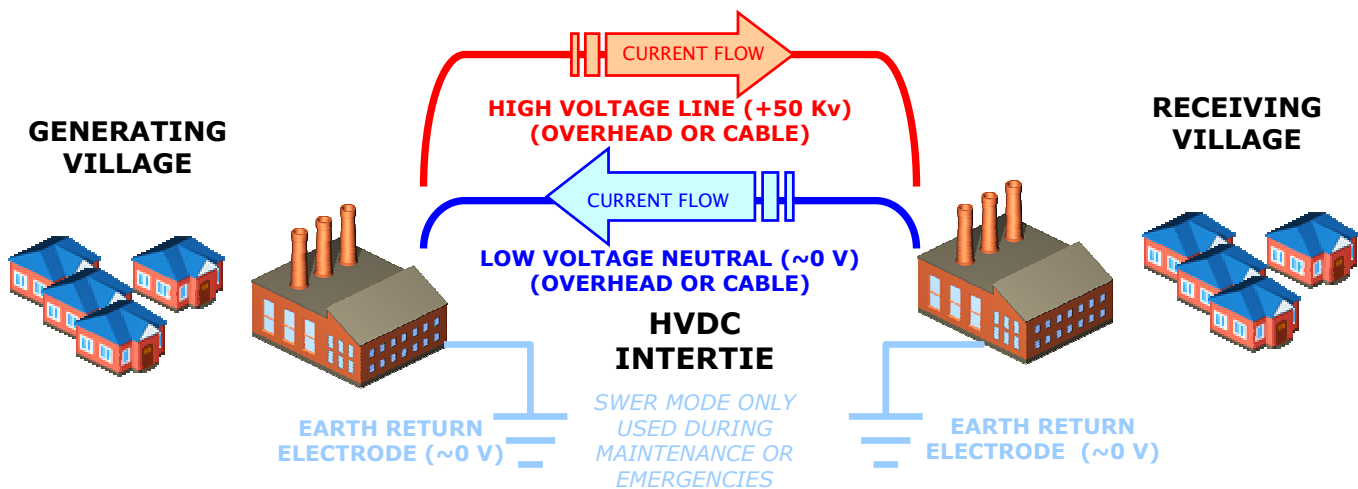


Figure 4-2: Monopolar HVDC Intertie With Return Conductor (SWER-capable for backup)

4.1.3 Bipolar HVDC

A bipolar HVDC intertie is generally the most costly and most reliable HVDC circuit configuration. It employs two parallel high-voltage conductors, one operated at positive voltage and the second at negative voltage. The system requires two converters at each end of the intertie (four total), compared to one converter per end for monopolar circuits (two total). Thus, the bipolar HVDC configuration includes these major components:

- Two AC/DC Converter modules in the generating village. One (+) and one (-).
- Two high voltage conductors. These could be overhead lines, buried cables, or submarine cables.
- Two DC/AC Converters in the receiving village. One (+) and one (-).
- Grounding electrodes in both villages. These will not normally be used to complete the intertie circuit, but they will be used to balance the system and for SWER operation during maintenance or emergencies.

The additional costs of a bipolar HVDC intertie are largely due to the additional converters and the second high-voltage conductor. A bipolar HVDC intertie will be roughly twice as costly as a monopolar HVDC intertie.

The principal advantage of a bipolar intertie compared to a monopolar intertie is increased reliability. If something breaks on one of the two poles, the other pole can be operated as a monopolar intertie. This will reduce the power transfer capability, but the intertie can continue to function.

For most remote Alaska applications, the additional cost of bipolar circuits are not justified. Installing backup diesel generators in villages would be more cost effective than constructing a bipolar HVDC intertie.

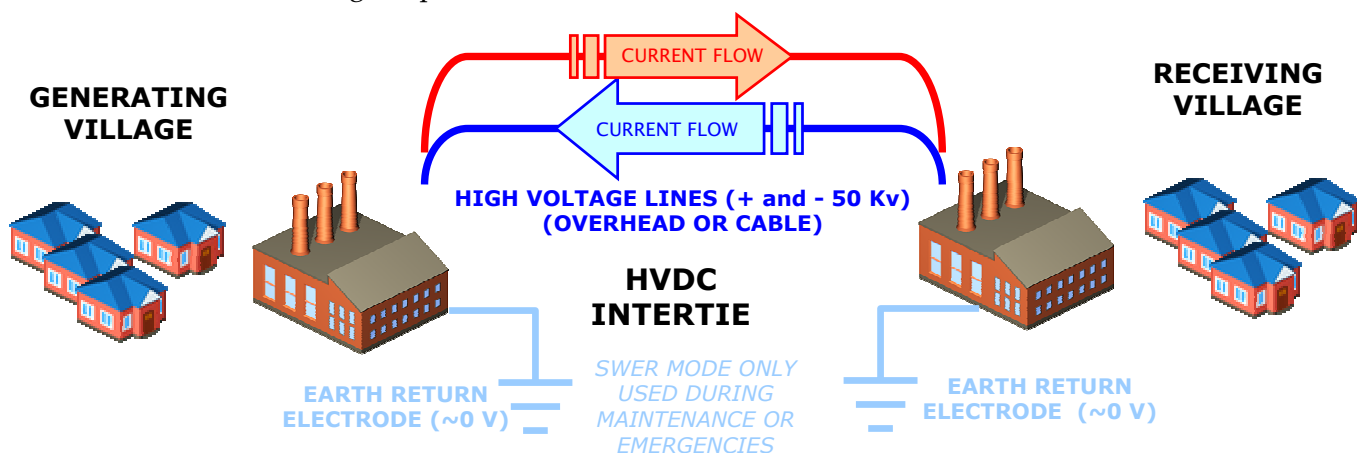


Figure 4-3: Bipolar HVDC Intertie (SWER-capable for backup)

4.2 DESIGN CONSIDERATIONS FOR SMALL ALASKA HVDC INTERTIES

Many of the technical aspects of designing and building small HVDC interties in Alaska are much the same as for building interties anywhere. The single dominating factor that sets construction in remote Alaska apart is logistics. Most projects have little or no support infrastructure, ranging from the basics such as modern lodging for workers to availability of transportation infrastructure, heavy equipment, skilled labor, and so on.

Many major construction projects address the logistical challenges of remote Alaska by importing everything necessary to get the job done by conventional means. This works, but is very costly.

A different solution to the logistics challenge is to tailor the design to use available local resources to the extent possible. This is a very challenging proposition, but the rewards – lower construction costs – are substantial. In general terms, designing for Alaska logistics means:

- Use materials and equipment that are readily shipped by common transportation methods, such as small cargo aircraft ¹². Use materials and construction methods that can utilize small, low ground pressure equipment to enable construction during summer or autumn thawed conditions.
- Use materials and construction methods that employ locally available equipment for transport and construction as much as possible.
- Reduce the amount of construction and fabrication required in the field and on the line. Pre-manufacture and pre-assemble before shipping to the villages or in the villages before shipping to the field to reduce costs and increase quality.
- Optimize the construction and assembly methods to employ locally available labor.

The design concepts presented in this Section have been developed using this philosophy.

¹² The largest cargo aircraft suitable for Alaska logistic planning is a Hercules C-130, but many village airstrips cannot accommodate a Hercules. A more universal cargo aircraft for remote Alaska projects is a Sherpa SD-330 or similar small cargo aircraft.



4.3 PERMITTING, REGULATORY, AND CODE CONSIDERATIONS

4.3.1 Environmental Permitting

Practically all remote Alaska HVDC interties will require permits from the state and federal resource agencies. In nearly all cases, intertie projects will have to go through the National Environmental Policy Act (NEPA) process, which may include an environmental assessment (EA) or a more involved environmental impact study (EIS) ¹³.

Common issues that come up in the permitting process for interties include:

- Aesthetics.
- Impacts to bird populations through birds hitting aerial structures and lines.
- Impacts due to lines located in parks, preserves, refuges, and similar areas.

In many cases, HVDC interties will be easier to permit than AC interties because they can reduce or avoid some of the impacts of AC interties.

- Overhead HVDC interties will have fewer wires aloft than AC interties, presenting a reduced target for bird strikes.
- HVDC can use buried cables in sensitive areas, which presents no potential for bird strikes and has virtually no aesthetic impact.

4.3.2 Property Acquisition

Small overhead HVDC interties would have a similar easement requirement as overhead AC interties. Depending on the project, the easement requirement could be increased if overhead guyed structures, such as are presented in Section 4.6, are used.

Small buried cable HVDC interties, on the other hand, could be built in easements as narrow as 10 feet.

4.3.3 Code Issues – Monopolar SWER Circuits

The State of Alaska has adopted the 2007 National Electrical Safety Code (NESC). The 2007 NESC addresses DC transmission systems and allows for two-wire monopolar and bipolar HVDC circuits. The 2007 NESC does not allow the use of monopolar SWER circuits for routine use, but does allow two-wire monopolar and bipolar HVDC circuits to operate in SWER mode in emergencies or on a temporary basis ¹⁴.

¹³ Generally, projects on federal lands or receiving federal funds must comply with NEPA.

¹⁴ NESC, C2-2007, Part 215.B.5.a and b, and Part 314.C.4.a and b.



For many remote Alaska HVDC interties, SWER circuits can be safely used. SWER circuits have been safely and successfully used in similar regions for many decades ¹⁵. The significant savings possible with SWER circuits (lower construction costs and higher intertie efficiencies) warrant their consideration and use for Alaska applications.

Monopolar SWER circuits are key to achieving the considerable cost savings and benefits offered by remote low-power HVDC interties. If Alaska is to reap the benefits of HVDC technology, a process will need to be developed to allow the use and approval of monopolar SWER circuits. Developing this process will likely be incremental and may include the following steps:

1. For the first interties, project-specific waivers to the 2007 NESC can be issued.
2. As experience with monopolar SWER circuits is gained, a code amendment allowing the use of SWER for remote low-power applications in Alaska is warranted.

More information on this issue is presented in Appendix B.

¹⁵ Examples of monopolar SWER circuits in regions similar to Alaska include the Finno-Skan line between Finland and Sweden, and the 'Basslink', between mainland Australia and Tasmania. Both utilize on-shore grounding grids for the SWER circuit.



4.4 CONTROL, COMMUNICATIONS, PROTECTION, AND SAFETY CONSIDERATIONS

4.4.1 Intertie Control and Communications

A two-node monopolar HVDC intertie does not require communications capability between the converters to function. The converters are able to regulate power flow into and out of the HVDC intertie by monitoring the intertie voltage. However, communications may be desirable for a number of reasons:

- Communications would be of value in startup, or transition between manual and automated operational modes.
- Small interties with communications could dispatch generation assets to carry large discretionary loads.
- More complex transmission topologies (three-node or more) may require communications to manage power flow, generation assets, and/or large loads.
- Communications would improve fault detection capabilities for monopolar SWER HVDC circuits.
- Broad-band communications could be made available for telecommunications use, improving reliability or reducing costs of telecommunications in the communities served.

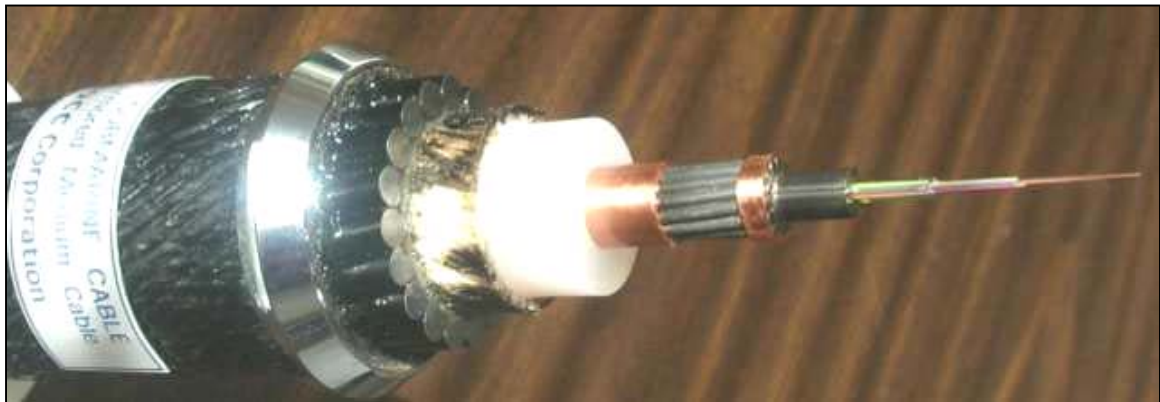


Figure 4-4: 1.5-inch Diameter Submarine Fiber Optic Communications Cable

A submarine HVDC cable with communications would be very similar in size and construction.

The communications bandwidth needed to achieve intertie control objectives is very modest. A carrier signal on the HVDC cable would provide sufficient bandwidth. Higher bandwidth communications would call for incorporating dedicated twisted-pair communications cable or fiber optics into the HVDC cable or overhead conductor.

4.4.2 Power Line Carrier Communications

Carrier communications systems use a coupling device and trap to induce a modulated carrier signal onto the power conductor. Carrier systems used on high voltage AC transmission circuits for long distances can transmit a few hundred bits of data per second, which is sufficient bandwidth for HVDC intertie control and monitoring functions. Carrier systems have also been used successfully on HVDC systems and would provide a viable dedicated communications circuit for HVDC intertie control and monitoring.

Broadband carrier technology has advanced considerably in recent years, and some commercially available broadband carrier systems are available for use on AC grids. Due to the higher frequencies necessary to achieve broadband data throughput, the range of these broadband devices is limited and may not span between villages without the use of repeaters. Also, broadband carrier systems designed for use on HVDC transmission circuits are not known to be commercially available at this time.

4.4.2.1 Dedicated Communications Cable

If high-bandwidth communications are desired, fiber optics are likely the best way to transmit information. Depending on the desired bandwidth, cable configuration, and intertie distance, twisted-pair communications cable may also be suitable. Fiber optic (FO) cable has sufficient capacity to provide true broadband communications between villages. Twisted pair cables may be able to serve this function, but signal attenuation and bandwidth would need to be analyzed on a per-intertie basis.

For overhead systems, a FO cable could be incorporated into the overhead conductor, a separate FO cable (or twisted-pair cable) could be wrapped around the HVDC conductor after it is strung and tensioned, using the conductor as a messenger, or a separate communications cable could be strung. For buried or submarine cable applications, a FO bundle could be incorporated to the HVDC cable internally or FO/twisted pair could be installed separately.

There are some advantages and disadvantages with adding FO cable to the overhead conductor. The internal FO cable option would increase the cable diameter, increasing static, wind, and ice loadings on the cable. Also, the lift capacity of readily available helicopters in Alaska limits the conductor length to about 2,000 feet per spool. This would require a significant number of FO splices, increasing the losses in the FO link and increasing construction costs for the line. The embedded FO cable would also complicate the repair of cable breaks.

The wound FO cable option would also result in a larger overall cable diameter. The presence of the FO cable on the outside of the conductor would increase wind and ice forces acting on the cable. This approach would reduce the number of splices necessary



in the FO cable, although splicing the FO cable would still be a complicating factor in repairing line breaks. Also, cable winding machines are designed to work on cables with suspension insulators. The simplest overhead HVDC line would use post top insulators, requiring a different or modified winding machine that could navigate around this type of insulator.

A third overhead alternative would be to use a separate FO cable. The viability of this approach would depend on the types of structures to be used.

4.4.3 Intertie Protection and Safety

Protective devices and software will vary depending on the configuration of each HVDC intertie system. Appropriate protective systems will be both site and system specific. The design phase of each HVDC intertie system will include a detailed analysis to determine the protection requirements for that system.

HVDC interties equipped for earth return operation will be able to monitor the current being transmitted and received over the HVDC intertie. A current imbalance would indicate a ground fault, and the system could be shut down. This protective capability would include hardware to measure and report current levels and software to interpret and compare current levels and order a converter shutdown when a fault condition is detected.

Other protective equipment on the HVDC interties may include:

- Lightning/Surge Arrestors on HVDC interties with overhead lines. Arrestors may be appropriate on interties using cables. Arrestors may also be used on the AC side of the converters to protect them from surges on the AC system.
- Fuses or breakers for protection from equipment faults. Fuses will only be used where the probability of their use is very low. A fault between the converter circuitry and enclosure might be such a case. This protective equipment will be selected by the converter designer.

Generally, the converters will function as breakers for the HVDC system. The architecture of the converter's power circuits and control software insures that converter failures cannot result in a 'failed closed' condition. Aside from possibly bleeding off energy stored in the high voltage capacitors, converter failures will result in a 'failed open' condition, and current will cease to flow until the failure is corrected.

When an external fault is detected by the converter controller, the controller can immediately interrupt power flow. The converter utilizes a fault detection routine that operates at 12 kHz. As an example, if the HVDC terminal of a converter experiences a



bolted fault to ground, this will be discovered on the next fault detection cycle, allowing the fault to last for no more than 83 microseconds before a fault condition is registered and the device is shut down.

In the unlikely event that the converter controller fails or freezes in an operating state, breakers on the AC side of the converter can be used to interrupt the connection to the AC system and thereby shut down power flow to or from the HVDC intertie. The other converter would automatically adjust its power transfer to zero by monitoring the line voltage or by direct communications.

4.5 HVDC GROUNDING GRID DESIGN CONSIDERATIONS

Any of the three HVDC intertie circuits – monopolar SWER, two-wire monopolar, or bipolar – will require grounding grids capable of transmitting the full intertie current (the current from one pole on a bipolar system) through earth return. On a one wire circuit, this is necessary for the intertie to function. On the two-wire circuits, this is necessary for safety and redundancy considerations.

4.5.1 Grounding Grid Siting

For a SWER intertie, proper siting of the grounding grids at each end of the line is critical. Soil resistivity can locally vary by several orders of magnitude, and grounding grids are best installed in relatively low resistance soils. Soils which typically have high resistance, and hence are poor locations for grounding grids, include:

- Permafrost
- Bedrock
- Highly granular and graded soils, such as washed gravel

In many remote regions of Alaska, the principal challenge in siting an HVDC grounding grid is permafrost. Fortunately, thawed areas do occur in most permafrost-rich regions of Alaska. These thawed areas may occur on south facing slopes, under lakes or rivers, or in abandoned river channels or taliks. Since most villages are situated along rivers, thawed ground suitable for HVDC ground grids will generally be available within a reasonable distance.

Soil conditions in the immediate vicinity of the grounding grid will determine the design of the grid. Depending on these conditions, the grid may have a step potential hazard and may need to be fenced or have other measures taken to protect personnel, the public, and wildlife.¹⁶

¹⁶ ANSI/IEEE Standard 80 has requirements for “Step and Touch Potential” limitations that would apply to grounding grid design and protective considerations.



Soil conditions farther away from the grounding grids are unimportant to the performance or safety of a SWER system. Once the current is safely dispersed into the ground in the immediate vicinity of the grid, it becomes extremely diffuse and can safely travel through any soil conditions.

4.5.2 Locating the Grounding System – Field Investigations

Field investigations will be necessary to determine the best location for the grounding grids. The first step will be a photogrammetric analysis to determine the local geological features. Since most villages are located near rivers, abandoned meanders and oxbows will often provide good candidate locations for grounding grids. South facing slopes and ancient filled-in ponds or lakes will also provide candidate locations.

When prospective locations are established, they will be prioritized depending on their location and features. Ground resistivity will then be measured to determine if the location is suitable and to provide information for design of the grounding system.

4.5.3 Corrosion

After public safety considerations, corrosion hazards are the most significant concern commonly associated with the use of SWER transmission circuits. If a SWER circuit is installed parallel to a buried metallic utility (e.g., a pipeline, unjacketed power or communication cable, or water main), it can induce a current in the object, causing rapid corrosion and leading to premature failure. This is a project-specific consideration and will need to be evaluated for any proposed SWER system. One of the reasons SWER circuits are well-suited to Alaska is that relatively few large buried metallic assets exist in the remote areas of the state. Generally, proper siting of the grounding grids will avoid any hazard to the limited utility networks within villages that would be connected by HVDC SWER interties.

4.5.4 Grounding Grid Conceptual Design

The grounding grids at each end of a one-MW 50 kV DC intertie will normally handle 20 amperes of current.¹⁷ The grounding grid will be constructed in an area of locally thawed ground. The below-ground interface between the thawed ground and the permafrost will provide a very large surface area for the earth current to flow into the permafrost, enabling the current to flow into the high resistivity permafrost soils without causing an excessive voltage rise in the earth return part of the circuit.

¹⁷ This is the same amount of current that typical household AC circuits are rated to carry.



The grounding grid will consist of a series of grounding electrodes made of materials such as Duriron¹⁸ or other material that is not readily subject to corrosion. The electrodes may be rods driven directly into the soil. To increase the effective contact area between the electrodes and native soil, the electrodes may be installed in drill holes backfilled with a suitable stable, conductive material. Coke breeze is frequently used for this purpose.¹⁹

The depth, number, and spacing of electrodes will depend on site conditions. Electrodes are commonly configured in linear, star, and ring formations. Because soil resistivity increases considerably when the soil freezes, the electrodes will need to be deep enough to contact thawed soils beneath the active layer. In some cases, it may be cost effective to thermally insulate the ground surface to minimize the depth of the active layer thereby using shallower electrodes.

As a practical matter, the grounding grid should be located in soils with resistivity of not greater than 5,000 ohm-cm. Higher resistivities would typically result in unacceptable losses through the grounding grid or impractically costly grid designs.

In most installations an overhead or buried insulated conductor will be used to connect the grounding grid to the ground terminal of the HVDC converter. The length and routing of this ground conductor will vary by project and could be miles long.²⁰

¹⁸ Duriron is a trade name for a silicon-rich iron alloy.

¹⁹ Coke breeze is a processed material derived from screening heat-treated coke. It generally consists of particles smaller than 10 millimeters, and it has a typical in-place resistivity of less than 1 ohm-cm.

²⁰ The southern terminal of the bipolar 3,100 MW HVDC Pacific Intertie in Sylmar, California has a grounding grid located 30 miles away in the Pacific Ocean. The northern terminal's grounding grid is a ring of electrodes about 3,400 feet in diameter near Celilo, Oregon.



4.6 DESIGN CONSIDERATIONS FOR SMALL HVDC OVERHEAD INTERTIES

For most overhead remote Alaska interties over about ten miles in length, monopolar SWER HVDC circuits will be a technically appropriate and least-cost intertie solution. Of course, no single conceptual design can begin to address the variety of design conditions present across Alaska. Each intertie will undergo a design process that will evaluate the design conditions and identify a preferred design for that project.

Section 4.6.1 presents environmental and technical criteria for overhead intertie design that are considered representative of Alaska conditions. These criteria are used in subsequent discussion of conceptual overhead intertie designs.

Section 4.6.2 discusses the uncertainty and perceived risks that are associated with building and operating an intertie in remote Alaska that uses new and innovative technology such as the HVDC converters or different types of overhead structures. Mitigating these risks is necessary for the HVDC technology to succeed in lowering intertie costs and energy costs in Alaska.

Section 4.6.3 presents a conceptual overhead intertie design that takes advantage of the unique attributes of HVDC SWER transmission to reduce the construction and maintenance costs of remote Alaska interties.

Section 4.6.4 presents conceptual methods for performing maintenance and repair activities on the conceptual overhead intertie design presented in Section 4.6.3.



4.6.1 Basis for Conceptual Design

Conceptual design values used for an overhead HVDC SWER transmission line are summarized in Table 4-1 and briefly discussed on the following pages. These design values are considered representative of typical conditions in Alaska and useful for developing a conceptual design. It is the responsibility of the design professional to determine if the conceptual designs and design criteria presented in this section may be applicable to any specific project application. It may be appropriate to adapt the designs described herein to other conditions by using shorter spans, different structures, or other adaptations as appropriate to accommodate differing situations.

Table 4-1: Overhead HVDC Transmission Line Conceptual Design Basis

Criteria	Design Value
NESC Design Class	Class B
Radial Ice	1-inch
Wind	120 mph at 70 feet height
Ground Clearance	NESC for 69 kV AC, roads in rural districts
Soils	Silt rich, water saturated, marginal permafrost
Peak Electrical Throughput	1 MW (1 MVA)
Operating Voltage	50 kV DC

4.6.1.1 NESC Design Class

The NESC provides safety factors based upon the judged importance of a transmission line. For most rural Alaska applications, villages will have backup generation available. These transmission lines are intended to reduce operating costs more than provide reliability, and a modest safety factor could be justified. However, because of the high costs of repairing a lightly constructed line and the likely duration and costs of an outage due to line failure, heavier line construction is appropriate. In light of these considerations, NESC Class B construction standards are adopted for the HVDC line conceptual design. Class B provides the most stringent design criteria and highest safety factors specified in the NESC.

4.6.1.2 Radial Icing

While the NESC does offer Wind and Snow Charts for Alaska, the detail in these charts is insufficient for design in many areas, particularly along the coast or near mountains, where local climate conditions vary considerably. The most poorly defined design criterion is icing potential. To quantify ice formation in Alaska, major utilities in the



state were queried to learn the design criteria for existing lines and how those lines have fared. The results of these inquiries are summarized in Table 4-2.

Table 4-2: Radial Ice Design Criteria Used for Existing Alaska Transmission Lines

Utility/Source	Location	Radial Ice
NESC Heavy	Code Design Criteria	½ inch
Golden Valley Electric Association, Inc. (GVEA)	Interior	1 inch ¹
Copper Valley Electric Association, Inc. (CVEA)	Interior/Southcentral Coast/Coastal Mountains	3 inch ²
Chugach Electric Association, Inc. (CEA)	Southcentral Coast/Coastal Mountains	½ inch ³
Nushagak Electric Cooperative, Inc. (NEC)	Southwest Coast	½ inch ⁴

1. Lines in GVEA's service territory are more prone to accumulations of hoar frost than true ice buildup. GVEA has measured the weight of hoar frost on its lines, and the reported design value is the water-equivalent as radial ice (Steve Haagenon, 2008).
2. The Glennallen-Valdez intertie used 3 inches radial ice on the coastal side of Thompson Pass, 1.5 inches in the coastal mountains, and 1 inch in the interior Copper Valley (Int'l Engineering Company, undated) (Steve Bushong, 2008).
3. The cited value is for the 115-kV transmission line from Anchorage to Cooper Lake on the Kenai Peninsula (this line was designed to NESC Heavy). CEA personnel report that they have had line failures due to ice and wind loadings on the transmission line to Whittier, but not the main line between Anchorage and Cooper Lake (Donna Grop, 2008).
4. NEC's lines are designed to NESC Heavy. While they report no failures, ice loads do reportedly bring their lines close to the ground (Ed Willis, 2008).

The ½-inch radial ice specified for NESC-Heavy is considered marginal for a conceptual design tailored to Alaska. Also, the extraordinary 3-inch radial ice used for the CVEA line south of Thompson Pass near Valdez illustrates the extreme loads possible in some areas. Based on this information, one inch of radial ice is considered appropriate for conceptual design of the Alaska HVDC transmission lines. This will be adequate for most design conditions in Alaska, and only select areas should warrant more stringent design criteria.

4.6.1.3 Wind

The American Society of Civil Engineers (ASCE) wind chart provides a general reference on the expected wind velocities in Alaska. For many cases, this chart is not sufficiently accurate to do an economic design. One solution is to obtain additional weather data and/or to query local residents. Wind gauges can be installed in suspect terrain if the



situation warrants. Given the cost of the intertie and the magnitude and cost of a wind-induced failure, it is good practice to obtain high-confidence wind data for design.

A design wind speed of 120 miles per hour is adopted for this conceptual design. Some localities (in particular along the coasts and in the mountains) will exceed this value, and other localities (including much of the interior) can use lower design wind speeds.

4.6.1.4 Design Clearance

The design clearance for the overhead intertie is 19.4 feet, which is for a rural line to ground ²¹. The conceptual design meets this clearance at the maximum sag condition, which is at final sag with full ice loading.

4.6.1.5 Soils

Water saturated, silt rich, marginal permafrost soils are used for the conceptual design. These soil characteristics are selected because they are some of the most challenging for transmission system foundations, and they are common in extensive portions of Alaska, in particular the Yukon-Kuskokwim delta region and the areas around Bristol Bay. The conceptual designs based on these soil conditions are readily adapted to superior soil conditions, such as colder permafrost, bedrock, or granular soils.

4.6.1.6 Power Throughput Operating Voltage

One-MW power throughput at 50 kV DC is used for the intertie design.

²¹ 2007 NESC, Section 232.C.1.a and Table 232-1. Most stringent of rural criteria (Item 4, agricultural/forest areas) is used.



4.6.2 Risks and Mitigation Measures for Demonstration HVDC Overhead Intertie

Phase III of this HVDC project will include design, construction, and operation of a demonstration HVDC intertie in remote Alaska. By its very nature, this demonstration project will involve the use of new and/or innovative technology. Alaska's utility industry, and in particular the utility that will own and operate the demonstration intertie, will need assurances that the HVDC SWER intertie will operate reliably and can be maintained and repaired in unforgiving Alaska conditions. This section explains how the HVDC project will address these concerns.

Phase II of the HVDC project is intended to advance the design of untested or innovative elements of the HVDC SWER intertie concept to a level where the utility industry will be comfortable constructing HVDC SWER lines. While the location and design of the demonstration intertie is not yet known, the key components specific to an overhead design that may concern utilities are known, and are listed below.

- SWER concept and grounding grids
- Innovative overhead structures, materials, methods

4.6.2.1 SWER Concept Risk Mitigation

To address concerns regarding the viability, safety, and functionality of the SWER concept, a SWER circuit will be constructed in permafrost country and tested during Phase II of the HVDC project. There are two general options for how this test may be performed.

If a suitable existing utility distribution line can be found and obtained for testing purposes, grounding grids could be installed and the line used to test SWER performance. For this test to be cost-effective and useful, a location on the road system and in permafrost country is desirable. Negotiations would be warranted with utilities that have systems in areas that meet these criteria.

If a suitable existing utility distribution line cannot be identified or obtained, this test could also be conducted using a temporary overland cable as the 'high voltage' conductor between the two earth return ground grids. The location criteria cited above would still apply, but the test sites could be any property with suitable surficial geology and adequate size to accommodate two ground grids at reasonable separation. Because the test objective is the earth return pathway, the 'high voltage' conductor would only need to operate at up to a few hundred volts, allowing commercially available direct current power supplies to be used.



4.6.2.2 Overhead Structure Risk Mitigation

To address concerns regarding the design, cost, construction, operation, maintenance, and repair methods associated with innovative overhead structures, prototype structures and foundations would be built and installed at a cold regions test site during Phase II of the HVDC project. While the test site would have road access to control Phase II costs, the methods and equipment used to install, maintain, and repair the poles would be suitable for remote work. Representatives from the utility industry would be encouraged to observe the field testing efforts and lend their expertise and insights to refining the design and methods tested.

In the event that Phase II testing results are considered insufficient to address the risks of building a HVDC SWER intertie, additional testing could be conducted, or the demonstration intertie could be designed to allow for conversion to a two-wire monopolar HVDC intertie or to a conventional three-phase AC intertie. Two possible ways to design for future conversion are described below:

1. The convertible intertie design might consist of cantilevered poles spaced for a three-wire intertie, but with only the post-top insulator and conductor needed for a SWER HVDC circuit initially installed. If the intertie needed to be converted in the future, a cross-arm, additional insulators and conductors could be easily installed.
2. Another convertible intertie design might consist of cantilevered poles at an increased spacing (e.g., 600 feet), post top insulator, and a single conductor for HVDC SWER operation. If the intertie needed to be converted in the future, additional poles could be installed to reduce the span (e.g., to 300 feet) and cross arms, additional insulators, and additional conductors installed to convert the intertie to a two-wire monopolar HVDC line or three phase AC line as desired.

If a convertible Phase III demonstration project is desired, the line-conversion requirement may steer the location of the demonstration project away from areas of the state with silt-rich warm permafrost soils. Locating the demonstration intertie in cold permafrost or gravelly soil conditions will facilitate a design that is more easily converted to two-wire HVDC or three-wire AC. These types of soils would also provide for better overland access for a second round of line construction.

Providing for conversion has the potential to erode the cost savings achieved with an HVDC SWER intertie. By careful selection of the demonstration project site and proper design of the intertie, the projected cost savings of the HVDC SWER approach can be wholly or partially preserved.



Avoiding the silt-rich permafrost regions would also diminish the value of the HVDC SWER concept, as there is considerable demand for remote interties in these regions and HVDC SWER lines have significant potential to reduce capital costs for such remote interties. It is the objective of this project to fully address industry reservations regarding use of HVDC or innovative overhead lines in Phase II. The more gradual approaches described above should be considered only if utility sentiments require these technologies to be 'phased in' in a more gradual manner.

4.6.3 Conceptual Design For Overhead SWER Circuits in Warm Permafrost Country

The conceptual design for a monopolar SWER HVDC intertie uses 70-foot tall, guyed fiberglass poles to support a single alumoweld cable at a span of 1,000 feet. This is a significant departure from existing conventional interties built in remote regions of Alaska. This design approach is supported by many reasons:

- The monopolar SWER circuit only requires a single conductor. This eliminates the need for cross arms to maintain conductor separations, simplifying the pole top. Since conductor slaps under galloping conditions are not possible, very long spans are possible. Also, the lateral and gravity loads on the structures are reduced, enabling use of lighter structures.
- Foundations in the silt-rich permafrost soils typical of Alaska are very costly. By using a single conductor, long span, and guyed poles, the quantity and thus overall cost of foundations are significantly reduced.
- Use of alumoweld static cable is possible because of the high voltage and low current of the intertie. The cable resistance is low enough to maintain acceptable losses, while the cable's strength allows the very long spans.

The net result of this conceptual design is significant potential cost savings as compared to conventional AC intertie construction methods in remote, silt rich permafrost areas. In areas with superior soils or other conditions, it may be appropriate and cost effective to use conventional overhead designs, adapting them as appropriate to HVDC.

4.6.3.1 Foundations

Because the guys carry most of the lateral loads acting on the pole, the pole's foundation mainly needs to support the vertical loads of the intertie and down forces from guy tension. These pole foundations can use screw anchors or micro piles designed for the specific loads and soil conditions. A representative pole foundation could be a six or eight-inch screw anchor driven to 20 or 30 feet. Manufacturer design guides (Almita, AB Chance, etc.) can be used to select foundation materials if loadings and site conditions are known. In some cases, it may be desirable to utilize thermopile screw anchors,



which will allow the screw anchor to engage and permanently freeze a large mass of soil in the active layer, thereby increasing the stability of the foundation.

The guy foundations can utilize the same materials and techniques as the pole foundations. Six-inch screw anchors driven to 20 or 30 feet would typically be adequate for guy anchors. Soil nails or conventional dead-man anchors may also be suitable for the guys, although a dead-man would require an excavator.

Thermal conditions are of great importance in the selection of guy anchors and pole foundations. The temperature of permafrost can be measured and used to guide foundation design. Colder permafrost is stronger and less likely than warm permafrost to thaw within the design life of the intertie. Global warming puts warm permafrost at increased risk of melting, which has profound impacts on foundation design and cost. Construction disturbance can change the surface albedo, which can increase heat flux into the ground and also cause permafrost melting.

The foundations considered for this system will address these considerations and work to minimize permafrost degradation. Pole foundations may utilize deep foundations with surface insulation and high reflective coatings, convective thermopile to remove heat from the ground and maintain the permafrost, or other methods.

Guy foundations will carry tension loads and can be installed deep enough that they are not susceptible to thaw. In areas with very deep active layers, screw anchors may be more practical for the guy foundations. Screw anchors may also be suitable for the compression pole foundations in such areas.

An important consideration for guyed structures in permafrost and muskeg-type soils is differential ground movement due to frost heave. If the foundation and structure design does not plan for frost heave, the poles may be skewed from plumb after a single season. If the differential ground motion is in an adverse direction, extreme instances of frost heave could overstress the pole and guy structure causing premature failure. In such areas, a tension spring on each guy can be used to relieve these forces and maintain guy tensions within design parameters. Intertie inspections may be warranted in susceptible areas in the year after an intertie is built to monitor and if necessary adjust guy tensions so the springs function per design.

The older intertie between Healy and Fairbanks uses guyed-Y structures in permafrost soils, and faced many of the same design challenges as the proposed conceptual design for SWER HVDC lines. Personnel at Golden Valley Electric Association, Inc. (GVEA), which owns and maintains this line, were interviewed regarding its performance. The original line used either concrete blocks in good soils or wood piles in weaker soils for the guyed-Y foundation. The wood pile tend to frost jack, and are being replaced with steel pipe as needed. Guy anchors are screw anchors installed from about 14 to 40 feet



depending on soils, and have performed well. They have had some structure failures caused when the wood pile foundations frost jacked to the point that they overstressed the tower and it collapsed. They have installed breakable links and guy loops to relieve these stresses and prevent such failures ²².

GVEA's experience with this intertie provides valuable insights on the long-term performance of guyed structures built on weak permafrost soils.

4.6.3.2 Structures

The conceptual design calls for hollow fiberglass poles. These poles were selected because they are light-weight; impervious to rot, UV decay, and corrosion; and can be field spliced, which simplifies shipping to remote locations. These attributes make the poles easy to transport and erect in the field with locally available equipment. These attributes also give the poles a long expected service life.

Existing commercially available fiberglass utility poles such as Powertrusion with some modifications will meet the structural requirements of this conceptual design. Existing fiberglass poles are not optimized to this application. It will be possible to achieve cost savings on a large HVDC intertie project by developing and testing new fiberglass pole designs to reduce the per-pole cost and weight.

4.6.3.3 Hardware

Metal fittings will be fabricated for the pole base, pole top, and mid-pole splice. These fittings will be designed to accommodate all standard pole configurations and attachment requirements. Fittings will likely be constructed from aluminum or galvanized steel.

4.6.3.4 Insulators

The conceptual design uses an insulator equivalent to a 69-kV AC post-top insulator. This insulator is 42 inches tall. Suspension insulators will be used at turns in the line and at dead ends. Lateral loads from the insulators will be carried by properly oriented guy lines on the opposite side of the pole.

Contamination of the insulator sheds is a special consideration for HVDC applications. Because the voltage gradient across the insulator is constant (as opposed to the varying gradient across AC insulators), the insulator has a greater tendency than a comparable AC insulator to collect and retain contaminants from the ambient environment. The

²² Personal communication with Greg Wyman of GVEA, September 5, 2008.



accumulation of contaminants can eventually create a short-circuit pathway, causing a ground fault on the HVDC intertie. As a result, increased creepage distance and hydrophobic insulator coatings are often used on HVDC insulators.

Insulators manufactured by NGK appear to meet these criteria. They have the maximum sized sheds that make the creepage distances much longer and use a silicon polymer for the non-structural part of the insulators. The cantilever load is carried by a pultruded fiberglass rod which can be bolted to the pole top assembly.

Intertie routing, such as avoiding coastal alignments, can also reduce contaminant buildup. In some climates, natural precipitation is adequate to remove contaminants from the insulator surfaces. In drier climates, such as the North Slope, periodic mechanical rinsing of the insulator surfaces may be necessary to remove contaminants.

4.6.3.5 Conductor

The conceptual design uses 19#10 alumoweld (AW) static wire or equivalent as the current-carrying conductor. This wire is usually used as a static wire for guying utility structures. Because of the long spans and low current of the HVDC intertie conceptual design, AW or a similar conductor is suitable for this application.

This particular AW conductor has a per-foot weight of 0.448 pounds, and an ultimate strength of 27,190 pounds. The conceptual design calls for design tension at 33% of ultimate, which is 8,970 pounds.²³ To allow for helicopter staging of the conductor, 2,000-foot spools of conductor will be used. Splices will be of the conventional compression type.

Advances in material properties may result in a conductor that is better-suited to this application than 19#10 AW. For example, a ¼-inch diameter conductor with the same strength and electrical properties as 19#10 AW would be significantly lighter and would have a lesser wind profile, enabling structure spacing to be increased.

4.6.3.6 Construction Methods

The key to realizing the cost-reduction potential of HVDC on remote Alaska projects is using appropriate construction methods. If construction methods are not adapted to exploit the advantages of SWER HVDC, much or all of the cost savings may be lost.

This example construction approach uses Hughes 500 type helicopters, which are commonly available in Alaska. These helicopters have a sling capacity of approximately

²³ Design data is for Okonite 7x3/8" aluminum-clad steel messenger cable.



1,000 pounds. Existing commercially available low ground pressure vehicles are not optimized for this application. The ideal vehicle would be similar to a hydraulically driven BB Carrier. The BB Carrier was a predecessor of Nodwells, but much smaller ²⁴. The hydraulic drive system can be used to power drills, winches, spades, impact drivers, and other on-board equipment used for line construction ²⁵.

The following narrative sets forth the general construction approach recommended for this conceptual overhead HVDC intertie design. Preferred construction methods for any specific intertie will differ from this approach and will affect construction costs.

1. Identify and procure property rights to the intertie alignment. Standard practices for this effort are appropriate and are not duplicated here.
2. Send an engineering crew and survey party to survey the line and determine pole locations in the field. Surveying and preliminary line design may be completed beforehand by remote methods (e.g., LIDAR survey). The engineering crew will conduct geotechnical testing at each pole site to determine the type of foundation required. As appropriate, the engineering crew may adjust pole locations based on encountered conditions.
3. Order and ship materials to the project site. Depending on the project, one or both villages will be used as the base of operations. It may be cost effective to pre-assemble pole or foundation assemblies prior to shipping to the project.
4. Prepare and install pole foundations. Depending on the project, pole foundations may be shipped ready-to-install or may require some assembly in the village. Once ready to deploy to the field, the foundations for each pole (pole base and three guy foundations) will be air-lifted to the pole site by helicopter. A small low-ground pressure vehicle will be used to install the foundations. Depending on the terrain, this stage may occur during the late winter or summer months. The ground vehicle will remain in the field, and personnel and consumables will be transported to the vehicle daily by air. This will reduce transit times.

²⁴ The BB Carrier was manufactured in the late 1950s and early 1960s by Bombardier. It is no longer in production, and they are quite rare today. They featured a gross vehicle weight of about 2,000 pounds, a payload capacity of about 1,000 pounds, and a ground pressure of less than one psi. Their drive train used a planetary transmission, maintaining power to both tracks during turns, which reduced the tendency of these vehicles to damage fragile tundra vegetation.

²⁵ A 20,000 to 30,000 ft-lb hydraulic impact driver head on a small boom would be useful for driving foundation screw anchors.



5. Prepare and assemble poles. This will occur in one or both villages and may include splicing the poles, attaching the pole top and base hardware, attaching the post insulator and stringing blocks, and attaching the guy wires and hardware. An assembled pole will be packaged in a manner suitable for air lift and clearly labeled so it is deployed to the proper foundation.
6. Pole installation. Each assembled pole will be air lifted by helicopter to the pole's foundation. The pole will be spotted on the ground by the helicopter and a ground crew. The ground crew will use an A-frame and their small low ground pressure vehicle to erect the pole using two of the guy anchors as hoist points. Alternatively, the helicopter could be used to more quickly erect and secure the pole. Once the pole is erected, plumbed, and guys tensioned, the crew will drive to the next foundation site. Depending on helicopter logistics, it may be cost effective to employ two ground crews for this activity. Ground crews and consumables will be mobilized to the line daily by helicopter.
7. Stringing and setting conductor. The stringing line would be deployed by helicopter. Once in place, conductor would be staged by helicopter and deployed by ground crews. A Hughes-500 can lift approximately 2,000 feet of conductor at a time. Once the conductor is strung, ground crews would ascend each pole to set, tension, and fix the conductor ²⁶. Armor wrap and vibration dampers would be installed at this time.

Probable costs for constructing the overhead intertie using this method are presented in Section 5 of this report.

4.6.4 Maintenance and Repair Methods

This section discusses the conceptual maintenance and repair methods that would be appropriate for the 'tall-pole long-span' HVDC SWER overhead intertie discussed in Section 4.6.3. While some topics may be generally applicable to the maintenance and repair of overhead interties, this discussion focuses on and is specific to this particular intertie design concept.

4.6.4.1 Downed Pole / Foundations

The independently guyed poles would be designed to withstand a conductor break, reducing the likelihood of a cascading structural failure of the intertie. In the event that a single pole required replacement, a new pole could be mobilized to the field by

²⁶ Ascending the fiberglass poles would not be by traditional 'spur and belt' methods. See Section 4.6.3 for a discussion of recommended ascender methods.



airplane. Depending on site conditions, the pole could be assembled in the village or in the field. Either way, the pole is light enough that it can be transported on a sled behind a snow machine or similar vehicle. Once all materials are on site, the new pole would be erected in the same means as during line construction.

In the event that new pole foundations were required, they would be installed in the same manner as for original construction. If a suitable low ground pressure construction vehicle is not stationed in the village, it would be small and light enough to be mobilized to the project with a Hercules or smaller aircraft.

4.6.4.2 Pole Top Activities

Fiberglass poles cannot be climbed using the 'spur and belt' method commonly employed to climb wood poles. Instead, a pulley and cable or rope system would be an integral part of the fiberglass pole. The pulley would be installed in the pole top, and the cable would travel down the pole interior. The line crew would bring a bosun's chair and winch apparatus to attach to the pole apparatus and use this system to lift a line man to the pole top for maintenance.

This approach offers several advantages compared with conventional pole climbing methods.

- The equipment and inherent safety of the approach enables less experienced crews to ascend the poles.
- Pole-top maintenance is easier or possible during colder weather or adverse conditions.
- Ascent, descent, and top-site work is faster because the crew is not as fatigued.
- Work is less physically demanding, reducing the likelihood of fatigue-related accidents.



4.7 DESIGN CONSIDERATIONS FOR SMALL HVDC BURIED CABLE INTERTIES

In many parts of Alaska, buried interties can have significant advantages compared with overhead interties. Some of these advantages include:

- Avoiding bird or aesthetic impacts in environmentally sensitive areas
- Avoiding avalanche-prone areas
- Avoiding exposure to high wind, icing, or other environmental loadings
- Avoiding flood-velocity hazards in flood-prone regions
- Potential for narrower easement and right-of-way requirements

HVDC is well-suited to electrical transmission by buried cable. The electrical and physical properties of cables for DC power transmission are generally superior to the properties required for AC power transmission.

4.7.1 Cable Properties

Because the DC voltage and current does not oscillate as with AC, there is no capacitance reactance in the cable. Therefore, DC cable distances are limited only by resistance, whereas AC is limited by capacitance. As the operating voltage increases, so does the charging current (on both AC and DC cables) and capacitive reactance (only on AC cables). Cable insulation on an AC cable must withstand the peak voltage, which is about 1.4 times the RMS voltage. Cable insulation on a comparable DC cable (equal energy throughput) must withstand the DC nominal voltage, which is comparable to the AC RMS voltage. This means a DC cable can have less insulation and is smaller, lighter, less expensive, and easier to ship and install than a comparable AC cable. Another consideration in cable insulation is the voltage stresses. AC cable stresses are determined by capacitance, whereas DC voltage stresses are determined by resistance.

4.7.2 Dielectric Material

One dielectric material (insulation) commonly selected for DC cables is ethylene propylene rubber (EPR) as its properties are somewhat different than the more widely used cross linked polyethylene. These properties include:

- EPR does not have to have low dielectric losses like AC cable would because the cable fields are relatively static.
- EPR has more stable resistance over a range of temperatures.
- EPR insulation will continue to act as a dielectric when wet.

An advantage of the last feature is that it can be re-spliced and function without problems if for some reason the cable gets wet and moisture is carried along the conductor. Cases where water has migrated distances along cable conductors have caused significant problems in determining how much cable to replace.



4.7.3 Overland Installation Risks and Considerations

4.7.3.1 Contraction Cracking

Direct burial overland cable installed in ground subject to contraction cracking (also known as polygonal cracking) may be ripped apart at the contraction cracks, causing intermittent faults or complete cable failure. Alaska utilities have learned this lesson the hard way and now typically avoid this problem by using overhead distribution systems in many villages.

On the North Slope, utilities have learned that steel pipes larger than about 2 inches in diameter are able to withstand contraction forces without damage. Smaller diameter cables and pipes are buried about 10 feet deep to avoid cracking damage. Deep burial works because the seasonal temperature variation decreases with increasing depth, so the size of the crack at these depths is much smaller.

Installing a miles-long transmission line 10 feet deep would be prohibitively expensive and therefore impractical. However, DC single conductor cable can be installed in polyethylene duct. The cable and duct can be installed at one time from a spool. Installation can be done with a frost bucket, chain trencher, or cable plow.

Materials and methods to overcome the susceptibility of small diameter cables to frost movement-related failures will be tested during Phase II of the project. The intent of these tests will be to demonstrate that cables can be successfully and cost-effectively installed in terrain susceptible to polygonal cracking and frost heave, thereby achieving utility-industry buy-in for installing buried overland HVDC interties.

4.7.3.2 Burial Depths

The minimum burial depth in the NESC for cable in duct is 18 inches. In isolated unpopulated areas, one foot burial may be adequate, and would lower installation costs. This can be changed by an amendment or project specific waiver to the NESC. The amendment or waiver would come from the Alaska Department of Labor and Workforce Development.



4.8 DESIGN CONSIDERATIONS FOR SMALL HVDC SUBMARINE CABLE INTERTIES

All of the advantages of overland buried cable interties also apply to submarine interties. Additional advantages of submarine cables include:

- Potential for simplified alignment acquisition process (submerged lands are exclusively owned by the State of Alaska to three miles off-shore, and the Federal government thereafter).
- Ability to interconnect to islands and across bays, lakes, and similar water bodies.
- Simple installation. Submarine cables are typically laid directly on the seabed.
- Less potential for controversy over the SWER application. Large scale monopolar single-wire sea-return circuits have been in service all over the world, including high-latitude locations such as Scandinavia, for over 50 years ²⁷.

HVDC cable will be very helpful for any location in Alaska that needs long passages in the water. This will be especially useful in Southeast Alaska.

²⁷ See Footnote 4, page 6.



5.0 PROBABLE COSTS AND ECONOMIC FEASIBILITY

While HVDC transmission offers several technical advantages over AC transmission (long distance cables, asynchronous interties, less aerial wire in bird flyways, etc.), the expected primary benefit is lower-cost interties. Therefore, understanding the magnitude and likelihood of potential cost savings of an installed HVDC transmission system relative to a conventional AC system is important to judging the value of this technology.

This section presents probable costs for major system components and presents initial and life-cycle cost comparisons between a conventional overhead AC transmission line and an overhead HVDC line to evaluate the cost savings potential of the HVDC system.

The outcome of Phase II design and testing activities will affect the costs presented in this section. Regulatory and permitting factors will also affect system costs. For example, using overland HVDC cables or the reduced aerial wire may simplify or make possible the permit authorization of projects, or can lower property costs for projects. Similarly, failure to secure state approvals for a HVDC SWER intertie would necessitate a two-wire HVDC intertie, which would raise costs compared to a HVDC SWER intertie.

To address the uncertainty in the cost savings potential of HVDC at this stage of the project, two overhead construction scenarios were considered in order to provide a range of potential savings. Both cost scenarios focus on overhead construction in the marginal permafrost country that covers much of Alaska. This is considered to be the most challenging terrain for overhead systems – where costs are the highest.

- Cost scenario 1 uses the innovative 'long-span tall-pole' SWER HVDC overhead intertie advanced in Section 4.6.3. This conceptual design aims to optimize HVDC to these difficult conditions, and represents the lower range of probable costs for overhead HVDC interties in remote Alaska applications.
- Cost scenario 2 uses existing construction practice for four-wire AC interties, minimally modified for two-wire monopolar HVDC operation. This design is proven in these difficult conditions, but is relatively expensive. This scenario represents the upper range of probable costs for overhead HVDC interties in remote Alaska applications.

Because a specific intertie project (Phase III of this project) has not been identified, the probable costs in this section are generalized. Probable costs are developed for a hypothetical 25-mile long intertie. The cost of any specific project will vary.

This section does not compare costs for buried overland or submarine cable applications. In very general terms, HVDC cannot compete with AC on short cable interties due to the



fixed cost of the terminals, and AC cannot compete with HVDC on long cable interties due to the cost and practicality implications of balancing cable reactance. Because there is little opportunity for these technologies to compete head-to-head, a direct economic comparison of cable costs is not warranted here.

Of course, HVDC cable interties can be used in lieu of overhead AC interties. The probable costs of HVDC cable interties in remote Alaska applications depend to a large degree on the outcome of testing proposed for Phase II of this project. Indications are that it may be comparable to costs for overhead HVDC interties presented herein.

To bracket the probable costs of remote Alaska HVDC interties, probable costs were prepared for three intertie scenarios.

- Section 5.1 presents probable costs for a hypothetical 25-mile overhead AC intertie, used as a basis of comparison for HVDC costs.
- Section 5.2 presents probable costs for a hypothetical 25-mile overhead SWER HVDC intertie. This cost assumes use of the innovative overhead structures discussed in Section 4.6.3
- Section 5.3 presents probable costs for a hypothetical 25-mile two-wire monopolar HVDC intertie, using conventional construction methods.
- Section 5.4 develops life cycle costs and cost comparisons between these three scenarios.

5.1 AC INTERTIE COST

Several AC interties have been built between remote Alaska villages in recent years. The per-mile installed cost of these interties has ranged from \$140,000 to \$400,000. Table 5-1 presents a probable cost for a hypothetical 25-mile intertie in remote Alaska.

Table 5-1: Probable Installed Cost for a Hypothetical 25-Mile Overhead AC Intertie

Item	Probable Cost
Intertie Terminal Costs (per terminal)	\$50,000
Per-Mile AC Intertie Cost	\$296,000
PROBABLE TOTAL INSTALLED COST FOR AC INTERTIE	\$7,500,000



5.2 HVDC INTERTIE COSTS – INNOVATIVE 'LONG-SPAN TALL-POLE' SWER INTERTIE

Probable installed costs for a hypothetical remote Alaska overhead HVDC intertie built using the 'long-span tall-pole' conceptual design advanced in Section 4.6.3 are presented in Table 5-2.

Table 5-2: Probable Installed Cost for a Hypothetical 25-Mile Overhead HVDC Intertie Using the 'Long-Span Tall-Pole' Conceptual Design

HVDC TERMINAL COSTS

Item	Probable Cost
Converter	\$250,000
Converter Enclosure	\$35,000
Interface with village power plant bus, switchgear, controls	\$35,000
Grounding Grid	\$125,000
Grid Property Acquisition	\$25,000
Design, Permitting, Overhead and Administration (20%)	\$94,000
Contingency (20%)	\$94,000
Probable Installed Cost per Terminal	\$658,000

OVERHEAD LINE COSTS (OVERHEAD SWER HVDC INTERTIE)

Item	Probable Cost per Mile
Materials	\$29,800
Shipping	\$14,900
Labor	\$26,200
Equipment	\$14,800
Property / right of way acquisition	\$5,000
Design, Permitting, Overhead and Administration (25%)	\$22,700
Contingency (25%)	\$22,700
Probable Installed Cost per Mile	\$136,100

INSTALLED COST FOR A HYPOTHETICAL 25-MILE HVDC INTERTIE (LONG-SPAN, TALL-POLE)

Item	Probable Cost
Intertie Terminals	\$1,316,000
Transmission Line (SWER HVDC Overhead Line)	\$3,402,500
PROBABLE TOTAL INSTALLED COST FOR HVDC INTERTIE	\$4,718,500



5.3 HVDC INTERTIE COSTS – CONVENTIONALLY CONSTRUCTED TWO-WIRE HVDC INTERTIE

Probable installed costs for a hypothetical remote Alaska overhead HVDC intertie built using conventional methods are presented in Table 5-3. These probable costs are developed by taking the costs presented in Section 5.1 for conventional four-wire AC intertie construction, and making incremental adjustments to reflect modifications for two-wire HVDC operation.

Table 5-3: Probable Installed Cost for a Hypothetical 25-Mile Overhead HVDC Intertie Using Conventional Construction Methods and Materials

Item	Probable Cost
HVDC Intertie Terminals	\$1,316,000
Per-Mile Cost of AC Intertie (Starting Basis for Two-Wire HVDC Intertie)	\$296,000
Less two conductors	(\$63,600)
Less AC insulators, cross arms, hardware	(\$21,120)
Less 33% of structures due to increased spacing (400 ft spans)	(\$17,490)
Add 2 HVDC 50 kV insulators, and hardware	\$17,600
Per-Mile Cost of Two-Wire HVDC Intertie Using Conventional Methods	\$211,390
25-Mile Transmission Line (Two-Wire HVDC Overhead Line)	\$5,284,750
PROBABLE TOTAL INSTALLED COST FOR TWO-WIRE HVDC INTERTIE	\$6,600,750



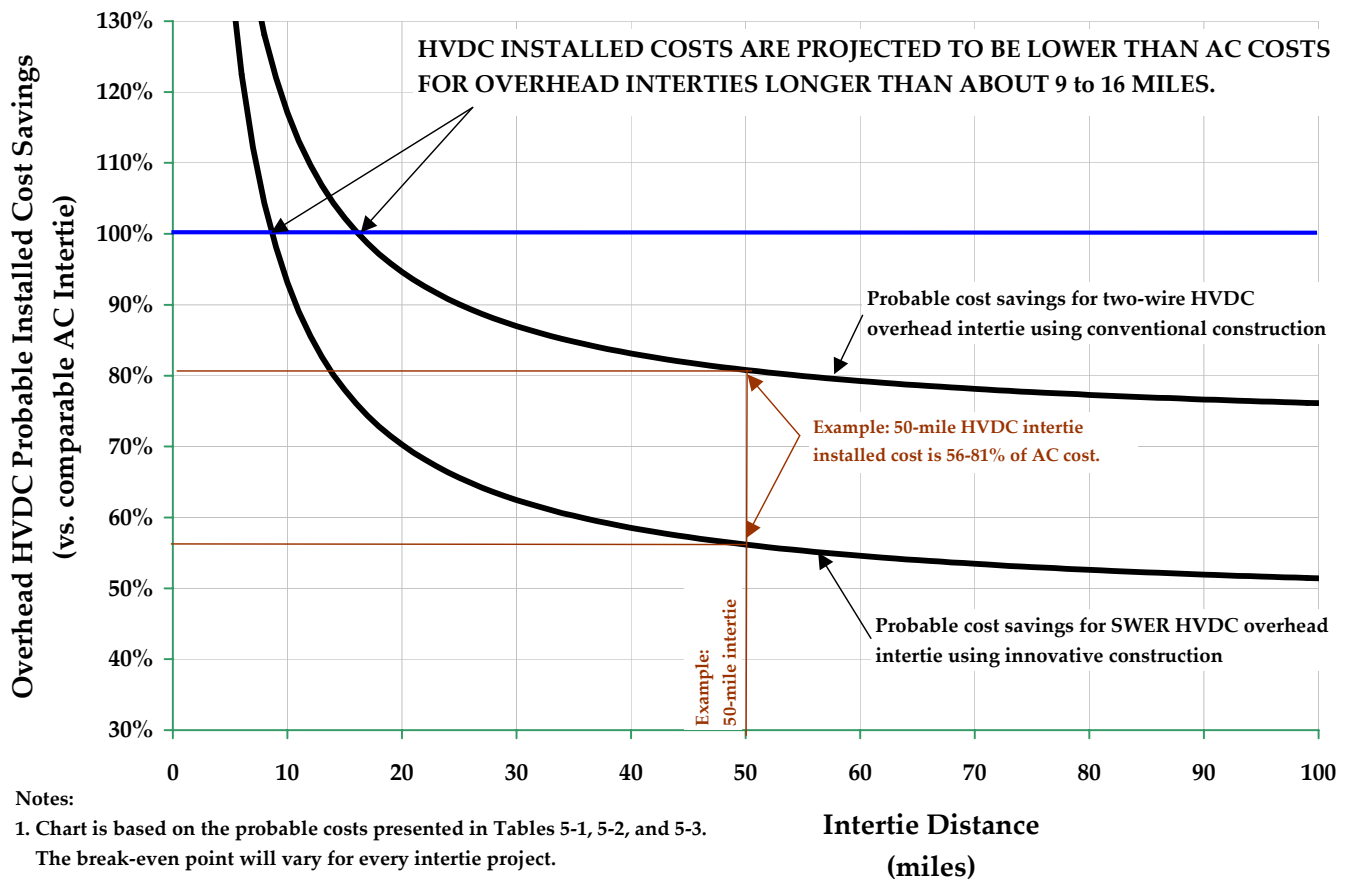
5.4 COST COMPARISONS OF HVDC AND AC INTERTIES

5.4.1 Comparison of Installed Costs

Because HVDC interties have relatively expensive terminals, very short HVDC interties will not be cost effective compared with AC interties. As the intertie length increases, the additional cost of the converters is made up by the lower per-mile costs for the transmission line. Thus, HVDC interties shorter than a certain threshold will be more costly than AC interties, and the savings potential of HVDC increases with the length of the intertie above this threshold.

The break-even point at which an HVDC intertie will be less costly than an AC intertie will vary from project to project. Figure 5-1 illustrates how the break-even point varies with relative intertie costs based on the probable costs presented in this section. From Figure 5-1, HVDC is expected to be less costly than AC for interties longer than 9 to 16 miles, depending on the type of construction used.

Figure 5-1: Comparative Probable Installed Costs of HVDC Interties vs. AC Interties



5.4.2 Comparison of Probable Life-Cycle Costs

The probable life cycle costs of a hypothetical 25-mile intertie built with conventional AC, SWER HVDC (Scenario 1), and two-wire HVDC (Scenario 2) were compared. Assumptions and probable life cycle costs are summarized in Table 5-4.

Table 5-4: Probable Life Cycle Cost Comparison of 25-Mile AC and HVDC Interties

Parameter	AC Intertie	SWER HVDC Intertie (Innovative ¹)	Two-Wire HVDC Intertie (Conventional ²)
Cost of Diesel (\$/gal)	\$7.00		
Generation Efficiency (kWh/gal)	13		
Intertie Efficiency	95.8%	93.4%	93.2%
Net Annual Energy Transmission (kWh)	1,664,400	1,664,400	1,664,400
Annual Transmission Losses (kWh)	72,970	118,521	120,839
Annualized Value of Transmission Losses (\$)	\$39,291	\$63,819	\$65,067
Intertie Design Life (years)	20		
Intertie Annual O&M Costs	\$56,000		
Effective Discount Rate	3%		
Present Worth of Transmission Losses	\$580,000	\$950,000	\$1,300,000
Present Worth of O&M Costs	\$830,000	\$830,000	\$830,000
Present Worth of Intertie (Installed Cost)	\$7,500,000	\$4,720,000	\$6,600,750
PROBABLE TOTAL LIFE-CYCLE COST	\$8,910,000	\$6,500,000	\$8,730,750
PRESENT WORTH SAVINGS (COST) OF HVDC VS. AC		\$2,410,000	\$179,250

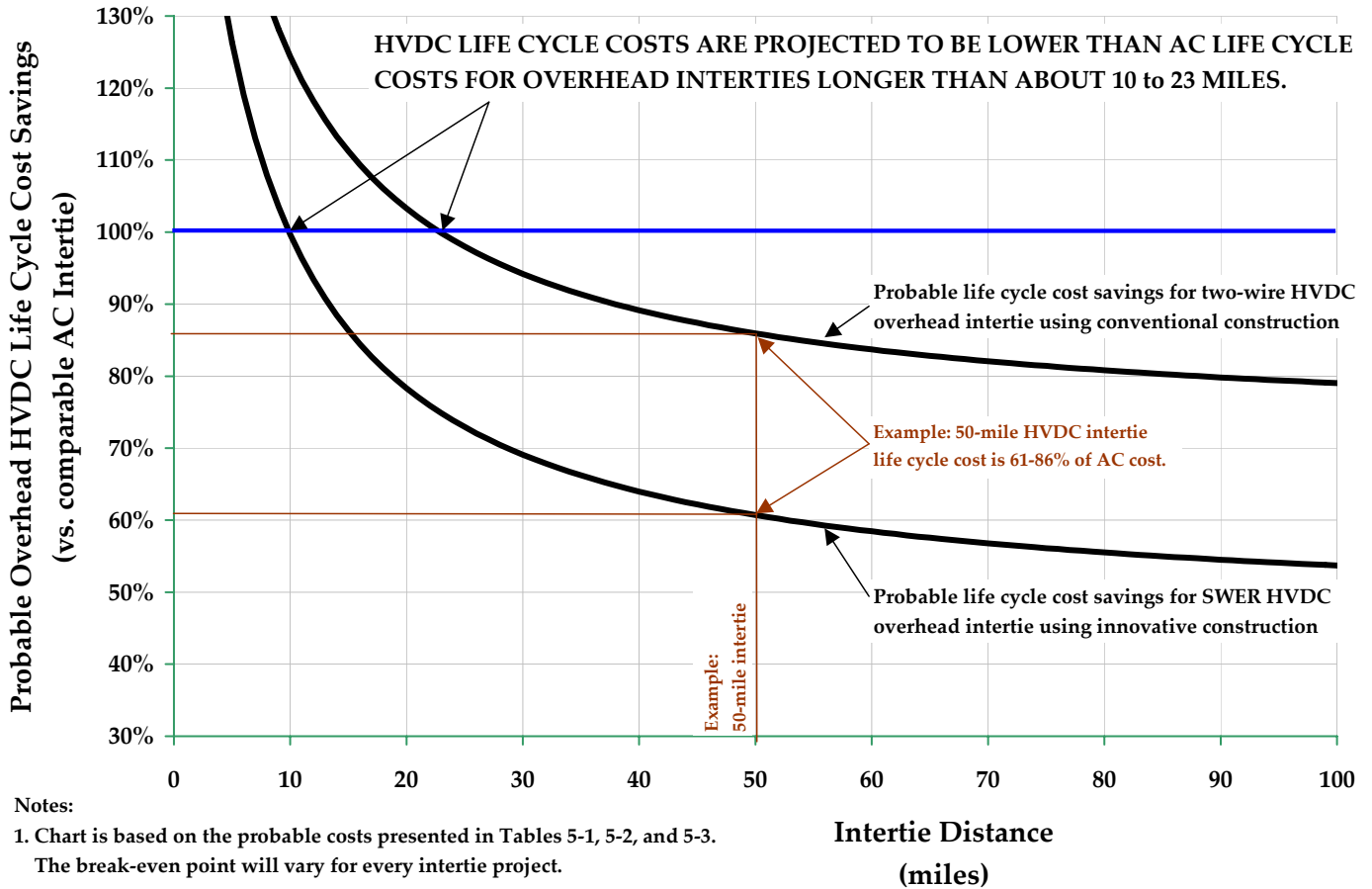
Notes:

1. 'Innovative' refers to the 'long-span, tall-pole' overhead HVDC concept advanced in Section 4.6.3.
2. 'Conventional' refers to conventional construction methods for four-wire AC interties used for remote Alaska interties, minimally adapted for a two-wire HVDC overhead intertie.

As Table 5-4 shows, a 25-mile HVDC intertie can be expected to have a probable present-worth life cycle cost of between \$6.5 and 8.7 million, depending on the design and construction methods. This is compared with an expected present-worth life cycle cost of \$8.9 million for a conventionally constructed AC line.

Even though the installed cost of the conventionally constructed HVDC intertie is significantly less than for the conventionally constructed AC intertie, the lower efficiency erodes some of this savings over the life of the line. As a result of this, the break-even point for this type of HVDC line construction occurs at about 23 miles. Figure 5-2 presents the relative costs for both HVDC construction scenarios as a function of intertie length.

Figure 5-2: Comparative Probable Life-Cycle Costs of HVDC Interties vs. AC Interties



6.0 PHASE II OF THE HVDC PROJECT

6.1 PHASE II OBJECTIVES AND SCOPE OF WORK

The objective of Phase I was to confirm the technical and economic feasibility of the HVDC transmission concept and system. Phase I has been completed and finds that continued development of the HVDC system is warranted.

Phase II of the HVDC Transmission System Project is intended to advance the design concepts and hardware developed in Phase I through full design, prototyping, and field testing. The intent of this effort is to advance the designs and concepts to the point that Alaska's utility industry is comfortable constructing a functional HVDC SWER intertie in Phase III of this project. Phase II work will include the following tasks:

- Work with stakeholders to identify a Phase III HVDC demonstration project in Alaska.
- Design, construct, and test fully-functional prototypes of the converter and transmission system components. This will validate operating efficiencies, costs, and functionality of the converter systems.
- For new or innovative system components, advance the design concepts developed in Phase I to final component designs.
- Construct, assemble, install, and field-test key transmission system components and representative assemblies as needed to test the assemblies and proposed construction and installation methods.
- Develop estimated system costs and economic feasibility analysis based upon Phase II findings.
- Develop cost estimates for Phase III activities.

Phase III is the design, permitting, and construction of a demonstration project in remote Alaska. The project location will be selected as part of Phase II.

6.1.1 Project Scoping

During Phase II, project stakeholders will be engaged to select a location for the Phase III demonstration project. By selecting a specific intertie project, the Phase II effort can be tailored to address the specific technical issues pertinent to that project.



6.1.2 Converters

Princeton Power Systems will design the one-MW prototype converter modularly, in order to support incremental increases in capacity as needed. The Phase II converter will consist of multiple blocks of the HVDC demonstrator that was successfully prototyped in Phase I. Specific activities to be performed during Phase II include:

- Review and agree upon applicable design, testing, and compliance standards
- Review and agree upon all applicable packaging, performance, and safety requirements for production units.
- Perform computer modeling to verify the power electronics design and determine functionality requirements of control software.
- Use information from Phase I design, modeling, and testing to optimize and finalize converter mechanical design.
- Generate component, cable, metal, and system prints and select components and vendors.
- Develop specifications for protective hardware between the converter, AC, and HVDC lines.
- Generate 3D drawings and prints and approve drawings with customer.
- Modify control software for multi-module interleaved one-MW operation.
- Research power line communication systems for communication between field units, integrate into control systems.
- Procure and assemble one (1) one-MW Prototype unit for confidence testing.
- Perform Design Verification Testing and Confidence Testing (functional and fault testing) to verify the Prototype unit's adherence to performance and safety requirements.
- Perform full-power (one MW) 8-hour burn-in test using two (2) 500-kW units in a series AC to HVDC to AC configuration.

6.1.3 Transmission System

- Design overhead transmission system components.
- Design direct-burial overland cable system. Includes design of frost-cracking resistant cable, trenching, and installation methods.
- Procure / fabricate hardware.
- Procure / fabricate specialized construction and maintenance equipment.
- Procure / rent cold region test site for field tests.
 - Overhead field tests.
 - Foundations.
 - Pole performance.
 - Construction techniques, methods, equipment.



- Maintenance techniques, methods, equipment.
- Perform overland buried cable field tests.
 - Polygonal-type crack resistant cable testing.
 - Construction techniques, methods, equipment.
- Perform submarine cable analysis and pressure testing.
- Update line construction cost estimates and evaluate system economic benefits based upon Phase II test data.
- Report documenting efforts, findings, conclusions, and recommendations.

6.2 PHASE II SCHEDULE

Estimated time required for completion of Phase II is 14 months from contract start date, pending confirmation of certain long lead parts and equipment availability for assembly of the converter modules. Also, certain aspects of the transmission system testing program require cold weather conditions and are thus subject to seasonal constraints.

6.3 PHASE II BUDGET

The Phase II budget is presented in Table 6-1.

Table 6-1: Phase II HVDC Project Budget

Task	Budget
Converter Design, Assembly, Testing	\$1,000,000
Transmission System Design, Fabrication, Installation, Testing	\$1,125,000
Project Management / Administration	\$125,000
Phase II Total	\$2,250,000



7.0 CONCLUSIONS AND RECOMMENDATIONS

Based upon the results of the Phase I project, the HVDC transmission system proposed for remote Alaska applications is technically feasible. Probable costs for the system indicate that HVDC transmission will be less costly than existing remote AC transmission systems for interties greater than about eight miles in length.

Based on the Phase I findings, continued work on the HVDC transmission system is warranted. This technology has significant potential to lower the cost of building remote electrical interties in Alaska. Such interties are considered critical to permanently reducing energy costs to Alaska's remote communities.

In addition to proceeding with Phase II of this project, the following activities are recommended for continued action and attention:

- Work with stakeholders to define a project for Phase III of this project and also to incorporate this technology into the State's master planning efforts for energy planning and policy. This HVDC technology can be ready for widespread commercial application as early as 2011, and the state should be prepared to use it. The survival of many of our villages may well depend on it.
- Continue to develop a statewide energy plan. The energy plan needs to consider the implications of affordable HVDC transmission interties, as it will dramatically change the outcome of the planning efforts for Alaska's remote communities. Local interties, larger energy projects, and lower energy costs are a natural outcome of a more affordable transmission system.
- Start to identify and secure transmission alignments for the necessary interties. Also, long-lead generation projects need to be prioritized and initiated.
- Build stakeholder support for state amendments to the NESC that will allow use of SWER circuits under appropriate conditions. If used properly, SWER circuits will reduce the installed costs of remote transmission systems without any negative impacts.
- Research communications options that may be able to be combined with HVDC and other intertie systems.



APPENDIX A – PHASE I HVDC DEMONSTRATOR AND PHASE II CONVERTER SPECIFICATIONS



Alaska HVDC System Specification

Project # 31 – PolarConsult HVDC

Document # D000135-SPC

Document Owner: T. Stouffer

Revision History

Rev.	Date	Changes	Editor
1	06/26/08	(DRAFT) Initial release	TS
2			
3			
4			
5			

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Requirement Types

H = Hard requirement. This spec must be met or beaten. Failing to meet the spec would cause the product/project to fail contractual requirements or not be competitive in the market. Examples are cost limitations or MIL certification requirements.

I = Internal goal. Due to an internal decision, this requirement was set as a goal. If this requirement is significantly restricting the design options, it could be relaxed through some internal discussions.

E = External goal. Due to a decision by the customer, this requirement was set as a goal. If this requirement is significantly restricting the design options, it could be relaxed, but would require discussions with and approval by the customer.

D = Design decision. The spec or design point was set in order to finalize the design. This design decision may be changed, but it could require both internal and external discussions and could delay the project with redesign work.

1 System Specs

Narrative Overview

75kW Battery backup inverter for industrial battery backup applications. Designed to be stackable to higher power levels with an external up-sized transfer switch setup. Must be UL approved.

General

Requirement	Demo Spec	Product Spec	Reason / Source
DC input voltage range	12 - 13.7 KV	48kV - 55kV	Polarconsult
Nominal Output Voltage:	480VAC 3-phase	480VAC 3-phase	Polarconsult
Nominal Frequency:	60Hz	60Hz	Polarconsult
Continuous Power rating (Phase II/III):	250kW @ 50C	1MW @ 50C	Polarconsult
Peak Efficiency:	TBD (Goal > 95%)	TBD (Goal > 95%)	PPS estimate
Safety Standards Compliance:		Designed to UL1741 standard	Industry Standard
Acoustic Level	85 db @ 3m	85 db @ 3m	PPS estimate

HVDC Port

Requirement	Demo Spec	Product Spec	Reason / Source
DC input voltage range	12 - 13.7 KV	48kV - 55kV	Polarconsult
Max HVDC current	21	21	Hardware Limited
HVDC voltage regulation	±5%	±5%	PPS estimate
Max DC Voltage ripple	±5%	±5%	PPS estimate
Max DC Current Ripple:	±1% (HVDC line length dependent)	±1% (HVDC line length dependent)	PPS estimate

AC Port - Grid Tie Mode

Requirement	Demo Spec	Product Spec	Reason / Source
Nominal Output Voltage:	480VAC 3-phase	480VAC 3-phase	Industry Standard
Output Voltage Range:	480VAC ±10%	480VAC ±10%	Industry Standard
Max Continuous Output current	332A rms	1330A rms	Polar consult
Nominal Output Frequency:	60Hz	60Hz	Industry Standard
Output Frequency Range:	59.3 - 60.5Hz	59.3 - 60.5Hz	UL-1741
Grid-tied Power Factor:	>.95 displacement (@ > 20% rated power)	>.95 displacement (@ > 20% rated power)	PPS Estimate
Grid-tied Total Harmonic Distortion:	<5% @ rated power	<5% @ rated power	UL-1741

AC Port - Microgrid Mode

Requirement	Demo Spec	Product Spec	Reason / Source
Output Voltage Regulation:	480VAC ±5%	480VAC ±5%	PPS equipment standard
Output Frequency Regulation:	±.01Hz	±.01Hz	Industry and PPS standard
Max Continuous Output current	332A rms	1330A rms	Polar consult
Allowable Power Factor:	.8 leading to .8 lagging	.8 leading to .8 lagging	PPS Estimate
Allowable THD:	50% Estimated	50% Estimated	PPS Estimate
Allowable Load Imbalance	100% (Derated Power Output)	100% (Derated Power Output)	Polar Consult

Protection

Requirement	Demo Spec	Product Spec	Reason / Source
Anti-Islanding Protection:	Current Vector Variation, (meets UL-1741)	Current Vector Variation, (meets UL-1741)	UL-1741
Over-current protection:	150% cutoff	150% cutoff	PPS
Surge suppression:	None	TBD	Industry Standard
Inrush protection:	DC bus pre-charge system	DC bus pre-charge system	PPS
HVDC	over/under voltage detection, 200% current limit	over/under voltage detection, 200% current limit Plus application specific fault detection	PPS/Polar Consult
Internal Fault detection	Component over-voltage, over-current, overtemperature, overload, and control system health faults	Component over-voltage, over-current, overtemperature, overload, and control system health faults	PPS

Environmental

Requirement	Demo Spec	Product Spec	Reason / Source
Ambient temperature (operating):	15-30C Ambient	0 - 50C Ambient	Industry Standard
Ambient temperature (storage):	-	-20 - 50C	Industry Standard
Humidity:	-	5 to 95% non-condensing	Industry Standard
Altitude:	-	0 - 3300ft above sea level	Less than industry standard, should we consider increasing this?

Enclosure

Requirement	Demo Spec	Product Spec	Reason / Source
Configuration:	NEMA 1 free-standing enclosure(s) and free-standing oil tank	NEMA 1 Free-Standing Enclosure	Industry Standard
Size:	-	TBD	
Conduit Entry:	-	TBD	
Cooling:	Oil/Forced Air	Oil/Forced Air	Industry standard

Interface

Requirement	Demo Spec	Product Spec	Reason / Source
Analog I/O:	3 0-10V Analog Inputs 1 0-10V/0-20mA Analog Output	3 0-10V Analog Inputs 1 0-10V/0-20mA Analog Output	PPS Standard
Digital I/O:	3 Digital Inputs 3 Relay Outputs	3 Digital Inputs 3 Relay Outputs	PPS Standard
Comm:	Modbus over RS-485	Modbus over RS-485	PPS Standard
Front Panel:	-	PPS standard Front Panel Interface	PPS Standard
Web UI:	Diagnostics and Control	Diagnostics and Control	PPS Standard

Demonstrator Functionality

Requirement	Spec		Reason / Source
DC->AC conversion (Grid-tied)	0 - Full Power operation from 12000VDC feeding into 480VAC grid connection		
DC->AC conversion (Resistive Load)	0 - 100kW		

2 Design Decisions

Notes

System

Requirement	Spec	Reason / Source	Type	Date

Power Electronics

Requirement	Spec	Reason / Source	Type	Date

Mechanicals / Packaging

Requirement	Spec	Reason	Type	Date

Control System

Requirement	Spec	Reason / Source	Type	Date

User Interfaces - I/O - Communications

Requirement	Spec	Reason / Source	Type	Date

3 Approvals

Customer _____ Date _____
 _____ - Polarconsult

Technical POC _____ Date _____

APPENDIX B – ADDITIONAL INFORMATION ON SWER AND CODE COMPLIANCE





polarconsult alaska, inc.

ENGINEERS • SURVEYORS • ENVIRONMENTAL CONSULTANTS

February 18, 2008

**DEPARTMENT OF LABOR AND WORKFORCE DEVELOPMENT
LABOR STANDARDS AND SAFETY DIVISION – MECHANICAL INSPECTION**

3301 Eagle Street, Suite 302
Anchorage, AK 99503

Subject: Request for Modification of 2007 NESC Allowing Use of SWER

Dear Mr. Al Nagel:

We respectfully request that the Department of Labor approve a modification of the 2007 National Electric Safety Code (NESC) allowing single-wire earth return (SWER) for alternating current (AC) and direct current (DC) transmission circuits within its jurisdiction. We have included the following for the Department's consideration:

1. Language of the proposed modification to allow SWER use.
2. Benefits of the proposed modification to allow SWER use.
3. Examples of successful SWER systems in Alaska.
4. Examples of jurisdictions and systems that enjoy the benefits of SWER systems.
5. Technical discussion and comparison of risks with earth return using NESC-compliant circuits and SWER circuits.
6. Definition of selected terminology.
7. Letter from Dr. Richard Wies, P.E., Ph.D. supporting the use of DC SWER in Alaska.

As explained on the following pages, this modification will allow significant benefit to Alaskans through less costly and more reliable electrical power, without any significant incremental risks compared with practices allowed under the 2007 NESC.

At the highest level, building codes function to protect people and property by establishing standards for construction and operation of the built environment. The standards in the code are developed based on consideration of the risks and rewards that may result from specific actions. At this level, codes are a subjective reflection of the values our society place upon life and property. All human activity entails risks of varying types and also provides rewards¹. In the case of this specific requested modification, we believe that the considerable potential rewards easily outweigh the inconsequential risk, and the code modification is warranted.

If you have any questions or require further details or information about this requested modification, please contact myself or Joel Groves, P.E. at 258-2420.

Sincerely,

Earle Ausman, P.E.
President

POLARCONSULT ALASKA, INC.

Attachments:

- 1) Letter from Dr. Richard Wies, P.E., Ph.D. supporting the use of DC SWER in Alaska.
- 2) White Paper for HVDC SWER Circuit between St. Mary's and Yukon Village (PCA, 2008).
- 3) Questions and Answers on the Proposed HVDC Intertie St. Mary's and Yukon Village. (PCA, 2008).
- 4) Proposal for Developing an HVDC Transmission System for Rural Alaska (PCA, 2007).

1. Language of Proposed Code Modification

We request the following modifications to the NESC, C2-2007 to allow the use of ground return for rural transmission systems. Relevant parts of the code to be modified are part 215.B.5.a, 215.B.5.b, 314.C.4.a and 314.C.4.b.

Part 215.B.5.a and Part 314.C.4.a:

~~Supply circuits shall not be designed to use earth normally as the sole conductor for any part of the circuit.~~

Supply circuits shall not be designed to use earth normally as the sole conductor for any part of the circuit with the exception of rural transmission circuits designed by a registered professional engineer.

Part 215.B.5.b and Part 314.C.4.b:

~~Monopolar operation of a bipolar HVDC system is permissible for emergencies and limited periods for maintenance.~~

Monopolar DC using an earth return as designed by a registered professional engineer is allowed for rural transmission circuits.

These modifications will allow use of earth return circuits in rural Alaska, where significant economies and benefits to the public can be realized.

2. Benefits of the Requested Code Modification

2.1 Economic Benefits of SWER Transmission Circuits

The requested action is to modify the NESC to allow the use of earth return systems for electrical transmission circuits in Alaska. We will discuss herein the value of this modification to Alaska, most especially our rural areas but also to the state as a whole. The potential projects described below illustrate the value of this code modification to all Alaskans.

One of Alaska's most pressing concerns is the struggle of so many rural villages to pay for their energy needs. The costs of energizing and heating villages has become very expensive, and is endangering the continued existence of many villages.

Rural energy costs are high for many reasons, which include:

- Small size and geographic isolation require considerable duplication of generation and fuel storage facilities on a per-capita basis as compared with larger communities.
- Small populations and electrical loads result in relatively low-efficiency generators.
- Lack of economical nearby energy resources requires heavy reliance upon imported costly diesel fuel.

The solution to all of these contributing problems is electrical transmission. Affordable transmission circuits would enable multiple small villages to rely on a single generating plant and bulk fuel facility for electrical generation, and would enable that plant to use higher efficiency generators. Also, transmission circuits, combined with the larger loads and economies of scale offered by several interconnected villages, could be used to reach out to local and renewable energy resources, reducing the dependency on imported diesel.

Unfortunately, the existing 3 phase AC transmission circuits that have been built in rural Alaska are costly, up to \$300,000 per mile, and are not an economical solution for many villages. These 3 phase AC circuits have also had reliability problems in rural Alaska.

By comparison, using AC or DC single wire earth return (SWER) under the proposed code modification should reduce transmission costs by up to 50%, and should reduce maintenance costs and increase system reliability. This would enable a significant number of communities to lower their energy costs by tapping local energy resources, eliminating redundant infrastructure, and utilizing higher efficiency generation.

These cost savings will be achieved through a number of mechanisms, including:

- Overhead lines are reduced from three wires to just one wire.
- Support structures must carry simpler and smaller loads, resulting in simpler, less costly structures and foundations.
- Conductor-conductor spacing and clashing issues are eliminated, allowing longer spans and reducing the number of structures and foundations required.
- Less hardware, less materials, and fewer connections result in lower costs, but also in fewer things to go wrong, increasing reliability and reducing operating and maintenance costs over the life of the system.

In addition to the economic benefits offered by SWER transmission circuits, DC SWER in particular offers several important technical advantages that can benefit Alaskans:

- DC transmission circuits can run in cables for long distances. The length of a practical AC cable is limited by the cable capacitance, which reduces the amount of real power that can be transmitted as the cable length increases. In many regions of the state, cables are likely the most economical means to interconnect villages, but are only feasible with a DC circuit design, and only affordable using SWER operation. Submarine cables are a logical choice for transmission in Southeast Alaska. Also, buried cables may be the lowest cost, environmentally preferred approach for transmission in southwestern Alaska and the Yukon-Kuskokwim Delta, where bird strikes on aerial conductors are a permitting concern.
- DC transmission provides an asynchronous connection between villages. This simplifies interconnections.

2.2 Specific Alaskan Projects that Can Benefit from Using SWER

- The Denali Commission has funded Phase I of a project to connect the villages of St. Mary's and Mountain Village on the lower Yukon River via a 25-mile overhead high voltage DC (HVDC) SWER circuit. This project, which includes \$2.525 million in

one-time costs for development and design of the transmission and converter systems, will save over \$1.5 million compared with the expected costs for a conventional AC intertie between the two villages².

- Naknek Electric Association, Inc. (NEA) proposes to develop a geothermal generation plant. They are currently conducting exploratory drilling to characterize their geothermal resource. NEA has identified a 25 MW geothermal plant as the size necessary to be economically viable. This far exceeds NEA's load, and they have proposed to interconnect 25 communities over 25,000 square miles ranging from Illiama, Lake Clark, Togiak and south to Pilot Point via about 450 miles of transmission circuits to achieve a load sized to the geothermal plant. Using conventional 3-phase AC transmission, this grid is expected to cost around \$140 million. Using DC SWER transmission is expected to save up to \$70 million in initial construction costs, considerably improving the economics of this proposal. Most importantly, by making this project affordable to build, low cost renewable energy could be provided to 25 communities in southwestern Alaska, permanently reducing their exposure to volatile fuel prices and improving the economy and viability of these communities.
- Pilgrim Hot Springs north of Nome represents a geothermal resource that could be tapped to generate affordable and renewable electricity. The nearest logical market for this power is Nome, approximately 60 miles to the south. The most economical means of transmitting this power to Nome is via an SWER transmission circuit.
- The City of Galena proposes to install a 10 MW sodium-cooled package nuclear reactor. This 10 MW reactor far exceeds Galena's electrical load, and the project is not economical without providing the power to nearby villages. Using DC SWER cables or overhead transmission circuits is the lowest cost means of transmitting power from Galena to nearby villages up and down the Yukon River, and may be the only way to make this project viable.
- The community of Hoonah in Southeast does not have any nearby renewable resources, and they rely wholly on diesel for electrical generation. An AC cable has been proposed from the Greens Creek Mine and Juneau grid at a cost of \$29 million. A DC SWER cable should cost only about \$15 million. This lower cost can make this intertie economical to construct.
- Angoon is in a similar situation to Hoonah, and an SWER DC transmission circuit connecting Angoon, Takatz and Kake to the Tyee Project would be beneficial to these communities and less costly than the alternatives.
- There are many more rural interties that may be affordable using SWER circuits. Even connecting just two communities can save millions by retiring redundant bulk fuel facilities and power plants, significantly reducing the fixed operating costs that utilities must pass on to their customers.

3. Examples of SWER Circuits in Alaska

At least two SWER circuits have been built and operated in Alaska. As far as the SWER operational concept is concerned, both of these circuits were completely successful. For a number of reasons, neither circuit continues to operate in SWER mode today.

3.1 Bethel – Napakiak AC SWER Line

In 1981, a 10.5-mile 14.4 kV single phase AC SWER line was constructed to connect the small village of Napakiak to the City of Bethel. This line used bipod structures to suspend a 7#8 alumaweld conductor.

This line was constructed at a cost of \$23,000 per mile (1980 \$), and operated successfully for many years. Arguably, the line had two shortcomings, neither of which is related to its SWER operation: (1) the structural design of the line relied upon the conductor to provide longitudinal support to the bipod poles between dead-ends³, and on at least one occasion a conductor break cause a string of structures to fall down, and (2) over time, the load in Napakiak exceeded the line's capacity. However, the line was an unqualified success at demonstrating that SWER can reduce the costs of power transmission in rural Alaska.

The Alaska Energy Authority currently plans to reconstruct the Bethel-Napakiak line to a conventional three-phase line. Budgeted costs for this upgrade are \$264,000 per mile, about five times higher than the inflation-adjusted cost of the original line⁴.

3.2 Kobuk-Shungnak AC SWER Line

A 10-mile AC SWER line was constructed to connect the village of Shungnak to Kobuk in northwestern Alaska. The line and the SWER system worked successfully, however the support structures were constructed of local spruce timbers, and eventually the bases rotted. Like the Bethel – Napakiak SWER line, this line also successfully demonstrated SWER viability in permafrost regions⁵.

4. Other Jurisdictions Currently Using SWER Systems Allowed by the Proposed Code Modification

SWER transmission circuits have been employed for decades around the world on both AC and DC systems. In many regions and nations, it is accepted practice and proven technology. The same factors that make SWER so favorable in rural Alaska have also encouraged its adoption in many other rural and sparsely populated regions around the world.

4.1 Jurisdictions with Extensive Use of SWER AC Systems

Some nations that use SWER AC circuits are summarized below^{6, 7}.

- | | |
|---|---------------------------------------|
| ➤ Australia (>100,000 miles in service) | ➤ Cambodia (Electricite' du Cambodge) |
| ➤ New Zealand | ➤ Vietnam |
| ➤ Laos (Electricite' du Laos) | ➤ South Africa (Eskon Distribution) |

- Saskatchewan
- India
- India
- Brazil

4.2 Examples of Monopolar (SWER) DC Projects

A list of selected existing SWER DC projects is provided below ⁸. Note that most of these projects operate at significantly higher voltage and power throughput than would be required for most SWER interties in Alaska. These systems date from as early as 1954 (the Sweden-Gotland Line), and have operated successfully for decades. Some of the systems listed below have been upgraded to bipolar systems to double their capacity, but successfully operated as monopolar systems for years or decades.

- Swedish Mainland – Gotland Island: 20 MW, 100 kV, monopolar submarine cable with sea return.
- Sweden – Denmark – Germany (Konti-Skan Line): 250 MW, 250 kV submarine and land, On-shore grounding grids.
- Sardinia – Italian Mainland, Italy: 200 MW, 200 kV both earth and sea returns.
- Sileru – Barsoor Line, India: 100 MW, 100 kV with earth return.
- Sweden – Finland (Fenno-Skan Line): 500 MW, 400 kV, with sea return.
- Denmark – Germany (Kontek Line): 600 MW, 400 kV, sea and land
- Sweden – Germany, Baltic Cable: 600 MW, 450 kV, with earth return via deep hole electrodes.

5. Technical Comparison of Current NESC Practice vs. SWER under Requested Code Modification

The 2007 NESC does not allow SWER for AC transmission, and restricts DC to operation with SWER only for emergencies or maintenance on a bipolar system. This section discusses the technical differences, similarities, and risks associated with NESC-compliant circuits and SWER circuits under the requested code modification.

5.1 Earth Currents in NESC-Compliant Circuits and SWER Circuits

Earth currents are normally present in existing AC and DC circuits allowed under the NESC. As discussed below, the magnitude of these earth currents is often larger than the magnitude of earth currents that would occur on a typical AC or monopolar DC SWER circuit in rural Alaska.

5.1.1 Earth Currents in Wired-Ground AC Circuits

It is not commonly understood, but the neutral wire for a conventional AC system does not carry all of the return current. Because there are multiple ground points on any conventional AC system, a series of parallel return pathways are established: one over the ground wire, and additional pathways from each ground rod through the earth back to the power source. The current that flows via these pathways varies with the resistance of

each pathway. The earth pathways have a high resistivity, but very large area^a, and therefore a significant portion of the current can sometimes flow via the earth return on wired-ground systems.

5.1.2 Earth Currents in Bipolar DC Circuits

Pole-Balancing Earth Currents

The currents flowing in each line of a bipolar DC system are typically not perfectly balanced. Any residual currents are carried via earth return⁹. On large systems, these currents can be significant, and significantly larger than the earth return current on a small monopolar DC system serving Alaskan villages. As an example, a 1% imbalance on the 3,100 MW +/- 500 kV HVDC Pacific Intertie between Sylmar, CA and Celilo, OR, would produce a 31-ampere earth return current.

Temporary Monopolar Earth Currents

The NESC allows bipolar DC systems to operate in monopolar mode during maintenance or emergency episodes. In these instances, the full system current is carried via earth return. These temporary events can continue for months depending on the nature of the event. On a major line such as the Sylmar-Celilo Pacific Intertie, the current carried via earth return in this operational mode would be 3,100 amperes.

Co-existence with Other Transmission Circuits

Generally, earth currents from one transmission circuit have the potential to adversely affect the proper operation of adjacent transmission circuits. While this would not generally be an issue in Alaska (seldom would two parallel circuits exist in sufficient proximity to raise a concern), it warrants discussion.

The Pacific Intertie operates in parallel with two AC circuits. As discussed above, it occasionally operates in monopolar SWER mode, and does so without adverse affects to the AC circuits. Overall, energy transfer via the Pacific Intertie helps to stabilize the large interconnected energy grids along the West Coast.

5.1.3 Earth Currents in SWER Circuits

On an SWER system, all of the return current will run via earth return by design. For a small rural system, the amount of current may be less than the incidental earth currents that occur on a AC system, and certainly less than earth currents on major monopolar or bipolar HVDC circuits. For a rural Alaskan one MW HVDC circuit running at 60 kV, the earth return current would be under 17 amperes. For a similar five MW HVDC circuit, the earth return current would be about 83 amperes. This is less than the amperage serving a typical home.

^a The electrical resistance of a pathway is determined as the cross sectional area divided by the resistivity. Wire has a small sectional area and low resistivity, earth has a very large sectional area and high resistivity. It is not intuitive, but earth return paths can have similar resistance as wires. Usually, most of the resistance in an earth pathway is around the grounding rod, where the sectional area is smallest. Proper design of the grounding system is therefore very important to a successful earth return system.

5.1.4 Earth Currents and Utility Corrosion

DC SWER and Utility Corrosion

One of the principal reasons why the NESC restricts SWER for DC circuits is concern that the earth currents will find buried metallic utilities (pipelines, etc) and use them as a preferential pathway. When this occurs, the return current can induce a continuous oxidizing voltage on the buried utility, causing accelerated corrosion. This is a legitimate concern in areas where SWER DC circuits and buried utilities may coexist.

Bipolar DC systems reduce this corrosion risk by returning the current on a second conductor. This solution doubles the system's transmission capacity and cost by adding a second conductor and an additional two AC-DC converters. In rural Alaska, this additional capacity is not needed, so the bipolar approach just doubles costs, making interties less economic to build.

In rural Alaska, the concern over corroding buried utilities is generally unfounded, because buried metallic utilities do not exist where most SWER DC circuits would be installed. In villages with buried utilities, proper system design would insure the ground pathway would be located far enough away from the village to prevent this problem.

AC SWER and Utility Corrosion

AC SWER systems have much lower risk of inducing corrosion on metal structures because the induced voltage oscillates between a corroding and a protecting voltage.

5.3 Ground Faults in NESC Circuits and SWER Circuits

Ground faults occur when an undesired electrical pathway is somehow established between an energized conductor and the earth. This creates a safety hazard to the public, and it is very important to detect such faults and de-energize the system or correct the fault in a timely manner. As discussed below, the risks associated with ground faults on grounded and SWER systems are very similar.

When an energized conductor falls to the ground without breaking (so it continues to transmit power to the load), it may create a low-resistance or a high resistance fault to ground. Low resistance faults, as may occur by a conductor contacting the neutral wire, or landing in water or marshy ground, result in a very high current flow (a short circuit), and are more easily detected by fault detection devices. High resistance faults, as may occur by a conductor falling onto ice, snow, or frozen ground, may not result in any detectable change in current flow, and their timely detection presents real challenges for safe operation of both NESC and SWER circuits. The following discussion focuses on high resistance faults.

5.3.1 Ground Faults in NESC Circuits

For a conventional AC system, if an energized conductor falls onto a high-resistance ground and does not happen to touch the neutral conductor, there may be insufficient change in current or voltage to alert operators or protective relays of the problem. Further, for a 3 phase delta circuit with grounding at the transformers (a very common AC transmission circuit), one conductor can fault to ground generating earth return

currents too small to cause a fault indication. With three conductors, there is higher probability of this type of occurrence than for a one-wire single phase AC SWER or DC SWER system.

5.3.2 Ground Faults in SWER Circuits

On a SWER circuit, if the energized conductor falls to a high-resistance ground, there may be insufficient change in current or voltage to alert operators or protective relays of the problem. Since there is no neutral conductor, that particular ground pathway and fault indication, which is by no means a guaranteed detection strategy, is not possible. In this sole manner, a ground-faulted SWER circuit presents a slightly greater risk than a ground-faulted NESC circuit. For perspective, even the 3,100 MW +/- 500 kV HVDC Pacific Intertie has limited capabilities to detect high resistance ground faults.

This slightly greater risk must be weighed against the substantial benefits offered by the use of SWER. Also, it is worth noting that the NESC Code Committee does not find this risk unacceptable, since they do allow SWER operation of bipolar HVDC circuits for extended periods of time for maintenance or emergency.

5.4 Magnetic Fields

A DC SWER circuit will create a constant magnetic field immediately around the conductor. The strength of this field attenuates rapidly with increasing distance from the conductor, and at 10s or 100s of feet is small relative to the Earth's magnetic field. In some instances, shallow large capacity HVDC SWER submarine cables have been observed to deflect magnetic compasses in close proximity to the cable¹⁰. The comparatively low-current HVDC cables likely to be used in Alaska (10s of amperes for rural interties compared with 1,000s of amperes on major cables) would probably not generate magnetic fields strong enough to disrupt magnetic compasses.

In submarine applications, this issue would need to be considered in the design phase by technical analysis, proper cable routing, and addition of the cable to navigational charts to notify mariners of its presence and location. This would also serve to reduce the likelihood of cable damage by dragging anchors and other maritime hazards.

5.5 Step Potential

Any grounding system, be it for an NESC-compliant system, AC SWER, or DC SWER, must demonstrate through proper design (and if appropriate field testing) that it will not create an unsafe step potential. The technical considerations are the same for NESC-compliant and SWER systems. Indeed, the level of design, validation, and monitoring that would be employed on a DC SWER system would result in a higher degree of safety than for a small scale AC system that uses prescriptive design that may not be appropriate for some of Alaska's unique soil conditions.

Alaska's unique soil conditions, in particular the presence of high resistivity permafrost and seasonally frozen ground, will require careful design of grounding systems to control step potential. Proper site selection and design of the grounding systems can directly address these concerns. For example, thawed areas, such as river beds, lakes, or taliks,

are commonly found in close proximity to villages, and could make ideal grounding sites. Also, the actual footprint of grounding grids can be fenced or otherwise restricted to prevent the public or wildlife from encountering any step potentials within the grounding field.

6. Definition of Terms

AC:	Alternating current
Bipolar:	A direct current circuit that uses two wires to transmit energy. Bipolar circuits typically operate one wire at a positive potential and the second at a negative potential relative to ground (e.g., +/- 600,000 volts). These circuits normally also have an earth return pathway that is used to compensate for any imbalance on the two poles and also serve as a temporary return pathway if the negative or positive wire is out of service for any reason.
Circuit:	All electrical circuits provide an electrical pathway from a point of energy supply (e.g., a generator or battery) to a point of energy use, and then back to the point of supply. Without a complete pathway from supply to use and back, the circuit will not function. The pathway can take many forms. Most commonly it is made of metallic (copper or aluminum) wires, but it can also use water, the earth, or other materials. These other materials are usually used on the return pathway back to the point of supply.
DC:	Direct current.
Earth Return:	A means of completing an electrical circuit by using the earth as a return path instead of a second wire. This approach is frequently used in rural areas where (1) the cost to install a second wire for the return path is prohibitively high and (2) the lack of buried utilities ensures that technical issues with ground return are minimized.
HVDC:	High voltage direct current.
KV:	kilovolts, 1,000 volts.
Sea Return:	A means of completing an electrical circuit by using the sea (or more generally rivers, lakes and other water bodies) as a return path instead of a second wire. This approach is frequently used on submarine cables where the cost savings of not installing a second cable justify this approach.
Step Potential:	A voltage gradient that occurs at the ground surface due to earth return currents. If the voltage gradient is high enough, it can pose a hazard to people or wildlife stepping in the vicinity.
SWER:	single wire earth return.
Monopolar:	A direct current circuit that uses earth or sea return to complete the direct current circuit pathway. Monopolar lines have only one wire (one pole) transmitting energy. The return pathway is via the earth and/or water. A monopolar circuit is the same thing as a DC or HVDC SWER circuit.
MW:	Megawatt.

NEA: Naknek Electric Association, Inc.
NESC: National Electric Safety Code.

References on HVDC and SWER

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9. Polarconsult Alaska, Inc. "Questions and Answers on the Proposed HVDC Transmission System for Rural Alaska", April 2007.

ENDNOTES

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February 12, 2008

Dear Mr. Ausman:

Per the HVDC ground return project proposed by PolarConsult Alaska, Inc. to connect power systems in Alaska rural communities, I, Richard Wies, Ph.D., PE, a licensed professional electrical engineer in the State of Alaska (License #: AELE11793) recommend a local amendment to the 2007 NESC to allow HVDC ground return under the appropriate circumstances. The 2007 NESC currently allows for the use of ground return only for emergency operations, and sections 215.5.b. and 314.C4.b. need to be locally amended to allow HVDC ground return under appropriate conditions. The current language in these sections reads, "Monopolar operation of bipolar HVDC systems is permissible for emergencies and limited periods of maintenance." The suggested language for the proposed local amendment to the 2007 NESC as proposed by PolarConsult and amended slightly by Richard Wies, Ph.D., PE is, *"Exception: The use of monopolar DC is allowed for normal operations if it is designed in accordance with proper engineering practice taking into consideration specific site conditions including but not limited to public safety related to grounding and corrosion potential"*.

This local amendment to the 2007 NESC assumes that the grounding grid is properly established at both ends of the line with electrodes located in taliks, lakes, or old river beds (thawed areas). A properly established grounding grid should be in a thawed area below the active layer and connected to the ice rich permafrost and be located at a distance from villages and other buried structures to reduce the corrosion potential. The grounding area should also be enclosed by properly grounded chain-link safety fence.

Given the proposed HVDC ground return system and a properly constructed grounding grid, a local amendment to the 2007 NESC to allow monopolar DC systems under normal operations would not impose any significant hazard to the public and the environment. If you have any questions about this recommendation, please feel free to contact me by phone at 907-474-7071 or via email at ffrww@uaf.edu.

Best Regards,



Richard Wies, Ph.D., PE

Cc: Joel Groves